DOE/OR/21548-569

FEASIBILITY STUDY FOR REMEDIAL ACTION FOR THE GROUNDWATER OPERABLE UNITS AT THE CHEMICAL PLANT AREA AND THE ORDNANCE WORKS AREA, WELDON SPRING, MISSOURI

March 1998

prepared by
Argonne National Laboratory
Environmental Assessment Division

prepared for
U.S. Department of Energy
Weldon Spring Site Remedial Action Project
Weldon Spring, Missouri

and

U.S. Department of the Army
Corps of Engineers
Kansas City District
Kansas City, Missouri

STATE OF MISSOURI
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March 5, 1998

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NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Some acronyms used in tables or equations only are defined in the respective tables or equations.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

General

ACL	alternate concentration limit
AEC	U.S. Atomic Energy Commission
ARAR	applicable or relevant and appropriate requirement
BRA	baseline risk assessment
CFR	*Code of Federal Regulations*
COC	contaminant of concern
CSR	*Code of State Regulations*
DA	U.S. Department of Army
D&D	decontamination and decommissioning
DNAPL	dense nonaqueous phase liquid
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FR	*Federal Register*
FS	feasibility study (this document)
GAC	granular activated carbon
GWOU	groundwater operable unit
HGMS	high-gradient magnetic separation
IT	International Technology (Corporation)
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
NCP	National Oil and Hazardous Substances Contingency Plan
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
O&M	operation and maintenance
OU	operable unit
PCB	polychlorinated biphenyl
PRG	preliminary remediation goal
PVC	polyvinyl chloride
QWTP	Quarry Water Treatment Plant
RACER	Remedial Action Cost Estimating and Requirements System
RfD	reference dose

General (Cont.)

RH	relative humidity
RI	remedial investigation
ROD	Record of Decision
SWTP	Site Water Treatment Plant
TBC	to-be-considered (requirement)
TSP	total suspended particulate
UCL	upper confidence level
USGS	U.S. Geological Survey
UV	ultraviolet
VOC	volatile organic compound
WSCP	Weldon Spring Chemical Plant
WSOW	Weldon Spring Ordnance Works
WSSRAP	Weldon Spring Site Remedial Action Project
WSTA	Weldon Spring Training Area

Chemicals

Ca^{2+}	calcium ion
Cl^-	chloride ions
CO_2	carbon dioxide
1,2-DCE	1,2-dichloroethylene
1,3-DNB	1,3-dinitrobenzene
DNT	dinitrotoluene
2-amino-4,6-DNT	2-amino-4,6-dinitrotoluene
4-amino-2,6-DNT	4-amino-2,6-dinitrotoluene
2,4-DNT	2,4-dinitrotoluene
2,6-DNT	2,6-dinitrotoluene
Fe^{2+}	ferrous ion
F_2SO_4	iron sulfate
H_2O_2	hydrogen peroxide
O_2	oxygen
TCE	trichloroethylene
1,3,5-TNB	1,3,5-trinitrobenzene
TNT	trinitrotoluene
2,4,6-TNT	2,4,6-trinitrotoluene
UO_2	uranium dioxide

UNITS OF MEASURE

°C	degree(s) Celsius
Ci	curie(s)
cm	centimeter(s)
d	day(s)
°F	degree(s) Fahrenheit
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
g	gram(s)
gal	gallon(s)
gpm	gallon(s) per minute
h	hour(s)
ha	hectare(s)
in.	inch(es)
kg	kilogram(s)
km	kilometer(s)
L	liter(s)
lb	pound(s)
µg	microgram(s)
µm	micrometer(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
mg	milligram(s)
mi	mile(s)
min	minute(s)
mL	milliliter(s)
mm	millimeter(s)
mrem	millirem(s)
pCi	picocurie(s)
ppm	parts per million
s	second(s)
yd^3	cubic yard(s)
yr	year(s)

ENGLISH/METRIC AND METRIC/ENGLISH EQUIVALENTS

The following table lists the appropriate equivalents for English and metric units.

Multiply	By	To Obtain
English/Metric Equivalents		
acres	0.4047	hectares (ha)
cubic feet (ft^3)	0.02832	cubic meters (m^3)
cubic yards (yd^3)	0.7646	cubic meters (m^3)
degrees Fahrenheit (°F) -32	0.5555	degrees Celsius (°C)
feet (ft)	0.3048	meters (m)
gallons (gal)	3.785	liters (L)
gallons (gal)	0.003785	cubic meters (m^3)
inches (in.)	2.540	centimeters (cm)
miles (mi)	1.609	kilometers (km)
pounds (lb)	0.4536	kilograms (kg)
short tons (tons)	907.2	kilograms (kg)
short tons (tons)	0.9072	metric tons (t)
square feet (ft^2)	0.09290	square meters (m^2)
square yards (yd^2)	0.8361	square meters (m^2)
square miles (mi^2)	2.590	square kilometers (km^2)
yards (yd)	0.9144	meters (m)
Metric/English Equivalents		
centimeters (cm)	0.3937	inches (in.)
cubic meters (m^3)	35.31	cubic feet (ft^3)
cubic meters (m^3)	1.308	cubic yards (yd^3)
cubic meters (m^3)	264.2	gallons (gal)
degrees Celsius (°C) +17.78	1.8	degrees Fahrenheit (°F)
hectares (ha)	2.471	acres
kilograms (kg)	2.205	pounds (lb)
kilograms (kg)	0.001102	short tons (tons)
kilometers (km)	0.6214	miles (mi)
liters (L)	0.2642	gallons (gal)
meters (m)	3.281	feet (ft)
meters (m)	1.094	yards (yd)
metric tons (t)	1.102	short tons (tons)
square kilometers (km^2)	0.3861	square miles (mi^2)
square meters (m^2)	10.76	square feet (ft^2)
square meters (m^2)	1.196	square yards (yd^2)

1 INTRODUCTION

The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation to identify the appropriate response action to address groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively. The two areas are located in St. Charles County, about 48 km (30 mi) west of St. Louis (Figure 1.1). The groundwater operable unit (GWOU) at the WSCP is one of four operable units being evaluated by DOE as part of the Weldon Spring Site Remedial Action Project (WSSRAP). The groundwater operable unit at the WSOW is being evaluated by the DA as Operable Unit 2 (OU2); Operable Unit 1(OU1) addresses soil and pipeline contamination.

A remedial investigation/feasibility study (RI/FS) work plan summarizing initial site conditions and providing site hydrogeological and exposure models was published in August of 1995 (DOE 1995). Regulatory review of the remedial investigation (RI) and baseline risk assessment (BRA) has recently been completed. The RI (DOE and DA 1998b) discusses in detail the nature, extent, fate, and transport of groundwater and springwater contamination. The BRA (DOE and DA 1998a) is a combined baseline assessment of potential human health and ecological impacts and provides the estimated potential health risks and ecological impacts associated with groundwater and springwater contamination if no remedial action were taken.

This feasibility study (FS) has been prepared to evaluate potential options for addressing groundwater contamination at the WSCP and WSOW. A brief description of the history and environmental setting of the sites is presented in Section 1.1, key information relative to the nature and extent of contamination is presented in Section 1.2, and the results of the baseline risk assessment are summarized in Section 1.3. The objective of the FS is discussed in Section 1.4, and preliminary remediation goals are identified in Section 1.5. The organization of the remaining chapters of this FS is outlined in Section 1.6.

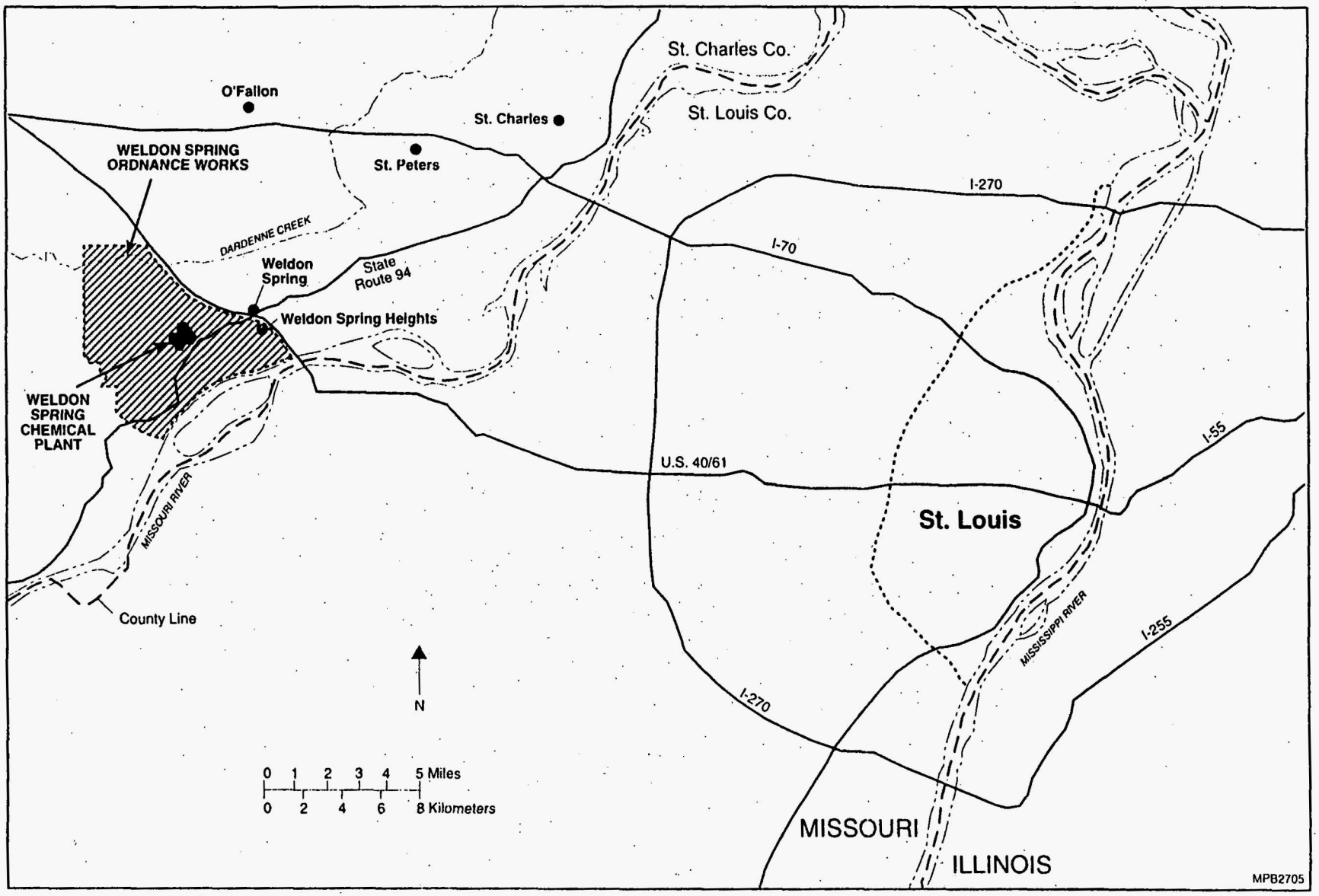

FIGURE 1.1 Locations of the Weldon Spring Chemical Plant and the Weldon Spring Ordnance Works

1.1 SITE BACKGROUND

1.1.1 Site History

The DA obtained the land for the WSOW by direct purchase and condemnation in the late 1930s from farmers and residents in St. Charles County. Following construction of the ordnance works, the Atlas Powder Company operated the facility from 1941 to 1945 to produce trinitrotoluene (TNT) and dinitrotoluene (DNT) explosives for use during World War II. In 1946, the facility was declared surplus property, and, by 1949, all but about 810 ha (2,000 acres) of the property (WSCP and Weldon Spring Training Area [WSTA]) had been transferred to the State of Missouri and the University of Missouri (International Technology [IT] Corporation 1993a).

The WSOW was listed on the National Priorities List (NPL) of the U.S. Environmental Protection Agency (EPA) in February 1990 (EPA 1990b). The DA is responsible for remediation of this site, as stipulated in the Federal Facilities Agreement (FFA) among the EPA, the DA, and the Missouri Department of Natural Resources.

In 1955, a total of 83 ha (205 acres) of the WSOW was transferred to the U.S. Atomic Energy Commission ([AEC]; a predecessor of DOE) for construction and operation of the Weldon Spring Uranium Feed Materials Plant, now referred to as the chemical plant (WSCP); an additional 6 ha (15 acres) was later transferred for storage of waste. The chemical plant was operated for the AEC by the Uranium Division of Mallinckrodt Chemical Works from 1957 to 1966 to process uranium and a limited amount of thorium ore concentrates. Waste slurries were piped to four raffinate pits, where the solids settled to the bottom; the supernatant liquids were decanted to the plant process sewer. This sewer drained off-site to the Missouri River via a 2.4-km (1.5-mi) natural drainage channel referred to as the Southeast Drainage.

In 1985, DOE assumed custody of the WSCP and designated the control and decontamination as a Major Project; it was redesignated as a Major System Acquisition in May 1988. In March 1989, the EPA listed the WSCP on the NPL (EPA 1989a).

1.1.2 Site Description

The original property of the WSOW encompassed a total area of 6,974 ha (17,232 acres). This property has since been divided into several contiguous areas with different ownership —

including the WSCP and quarry, WSTA, August A. Busch Memorial Conservation Area, Weldon Spring Conservation Area, Francis Howell High School and Francis Howell Administration Annex, community of Weldon Spring Heights, University of Missouri Research Park, St. Charles County well field, and Missouri Highway Department maintenance facility (Figure 1.2). The Army currently retains ownership of the 670-ha (1,655-acre) WSTA, which contains the majority of the former production facilities. Public access to the training area is restricted.

The potential source areas of groundwater contamination at the WSOW include the TNT and DNT production lines, three wastewater treatment plants, in-line settling tanks, burning grounds, sellite/acid plants, laboratory buildings, Mechanical City (facility maintenance area), regraining areas, underground toluene and wooden wastewater transport pipelines, and wastewater lagoons (Figure 1.3). Currently, the WSOW has relatively few of the 1,038 structures that constituted the explosives production facility. Most of the buildings were either burned or demolished during initial decontamination activities and subsequent cleanup efforts. Except for a few buildings on the WSTA, 100 storage bunkers, the residences in Weldon Spring Heights, and a few storage buildings at Francis Howell High School, only concrete foundations remain of the former WSOW. In addition, approximately 25,400 m (83,300 ft) of buried wooden pipeline is believed to remain in the WSTA.

The 88-ha (217-acre) WSCP lies within the boundaries of the WSOW. The original layout of the WSCP consisted of about 40 buildings, four waste retention ponds referred to as raffinate pits, two ponds (Ash Pond and Frog Pond), and two former dumps (north and south) that are in the process of being remediated (Figure 1.4). The area was contaminated by TNT and DNT production as well as by subsequent processing of uranium and thorium ores. The area is currently fenced to restrict public access. Burgermeister Spring, included in this operable unit, is located in the August A. Busch Memorial Conservation Area, directly south of Lake 34.

1.1.2.1 Geology

As part of site characterization, a number of investigations have been conducted at the WSCP and the WSOW to describe geological conditions (DOE 1992b; Rueff 1992; IT Corporation 1992a, 1993b; DOE and DA 1998b). Locally, the subsurface consists of unconsolidated deposits that unconformably overlie bedrock. Specific investigations at the WSTA and the WSCP have indicated

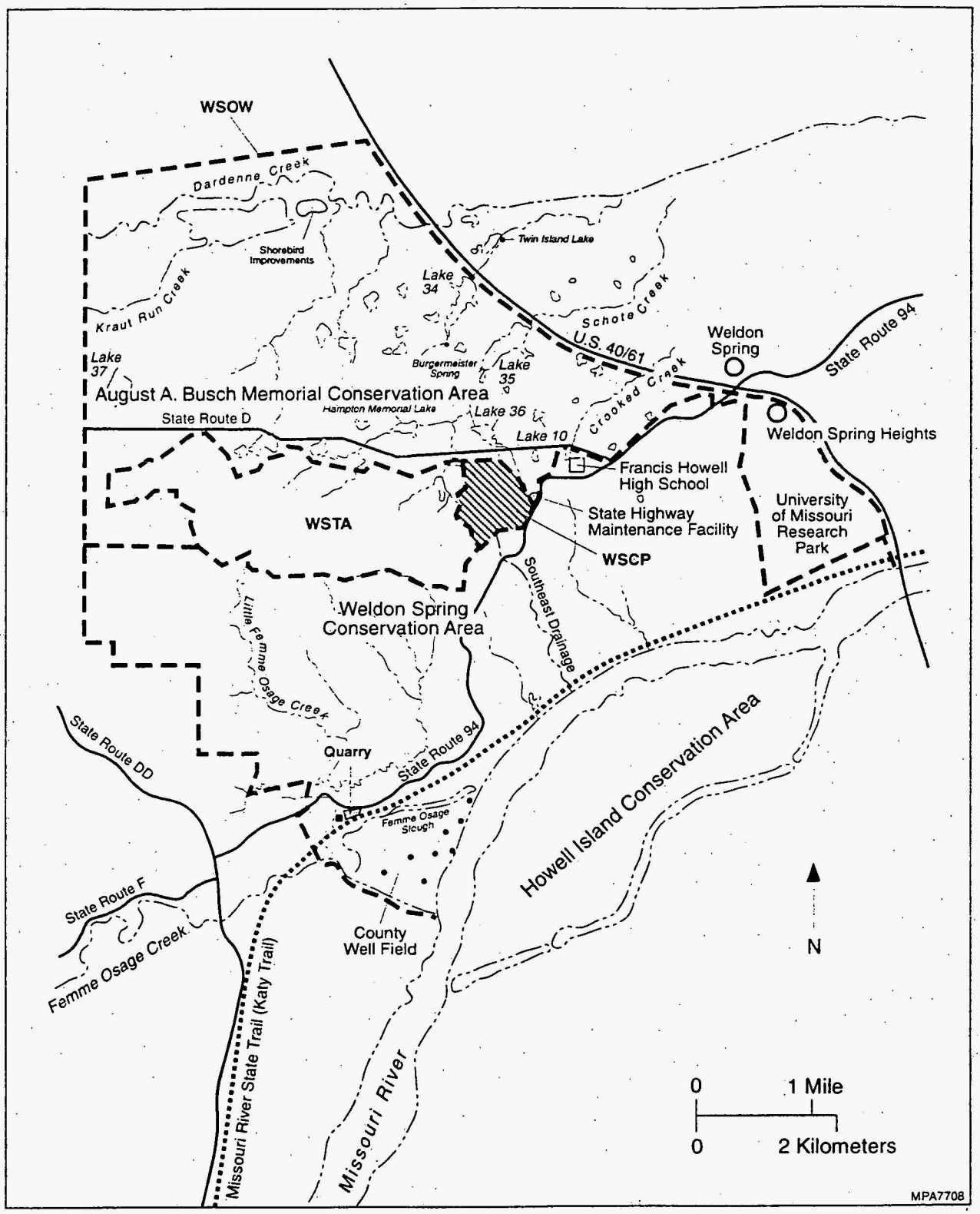

FIGURE 1.2 Map of the WSCP and the WSOW and Immediate Vicinity

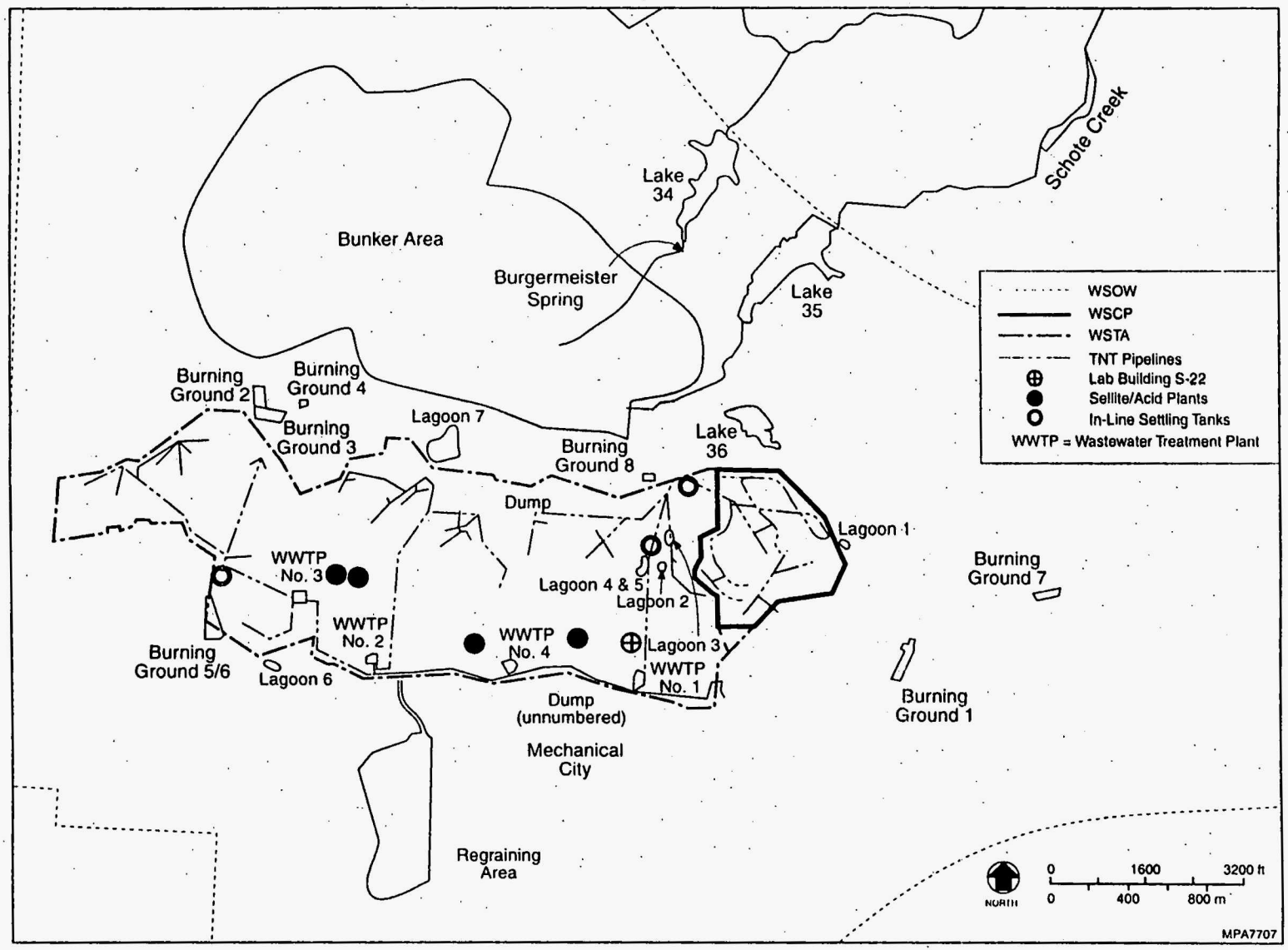

FIGURE 1.3 Locations of Waste Disposal Operations at the WSOW

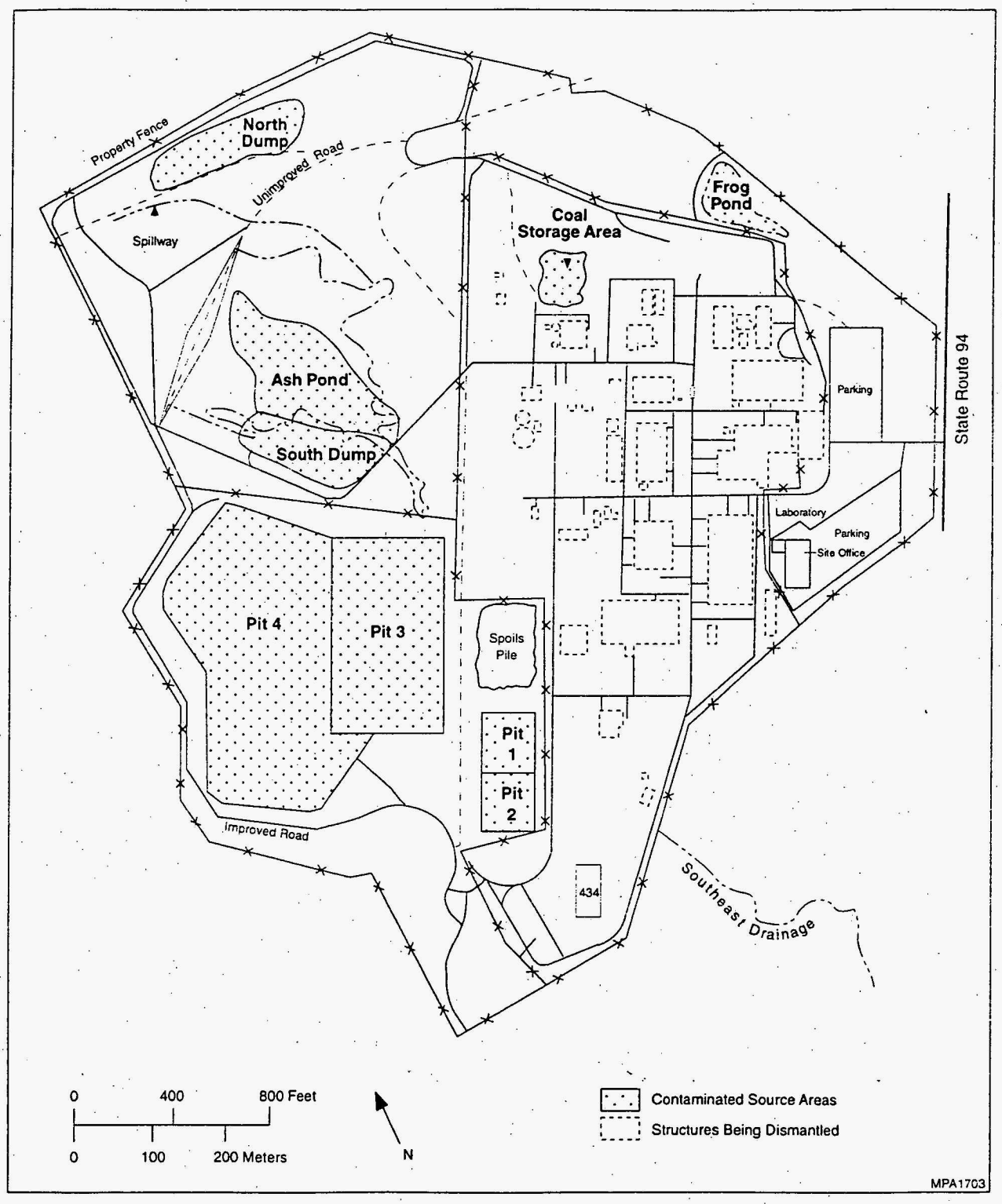

FIGURE 1.4 Original Layout of the WSCP

that the unconsolidated overburden consists mainly of modified loess, glacial drift, preglacial deposits, and residuum (Rueff 1992; DOE 1992b; DOE and DA 1998b). The thickness of the overburden deposits generally ranges from 0 to 21 m (0 to 70 ft) across the WSCP and WSOW (Mugel 1997). The variable thickness of the overburden deposits is controlled by both surface erosion and bedrock topography (DOE 1992b). Additional information on the overburden deposits can be found in the RI reports for various operable units at the WSCP and the WSOW (IT Corporation 1992a, 1993b; DOE 1992b; DOE and DA 1998b).

Beneath the unconsolidated Quaternary overburden deposits, the subsurface consists primarily of fractured and silicified carbonate units from the Mississippian, Devonian, and Ordovician Periods. Some sandstones and shales are also present (Table 1.1).

The uppermost bedrock unit and the primary focus of these GWOUs is the Burlington-Keokuk Limestone. On the basis of weathering characteristics, the formation has been divided into two zones. The upper zone, which is more weathered than the lower portion of the limestone, is referred to as the weathered limestone. The lower zone, which is less weathered, is identified as the unweathered limestone. The stratigraphic boundary between the two units is gradational.

On the basis of the estimated stratigraphic contact from rock cores and boring logs, the weathered limestone typically ranges in thickness from 0 to 34 m (0 to 113 ft) (Mugel 1997). The weathered unit is an argillaceous limestone, commonly containing as much as 60% chert as nodules, breccia fragments, and interbeds. The unit is moderately to highly fractured and slightly to severely weathered. Abundant iron oxide staining and manganese oxide occur in the rock matrix and along fractures.

At the WSCP, core sampling from the angled boreholes indicates that fracturing in the Burlington-Keokuk is predominantly horizontal and typically occurs along shaley interbeds, bedding planes, or chert interbeds. Solution features have also been found, which are typically partially or completely filled with clay and chert gravel. Although some voids occur in the uppermost bedrock, they are generally isolated and display limited vertical or lateral continuity (Garstang 1991).

In most cases, the unweathered unit underlies the weathered zone of the Burlington-Keokuk Limestone and is thinly to massively bedded and finely to coarsely crystalline and cherty. Both horizontal and vertical fracture densities are significantly lower in the unweathered unit than in the

TABLE 1.1 Generalized Stratigraphy and Hydrostratigraphy for the WSCP and the WSOW

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Characteristics	Hydrostratigraphic Unit[a]
Quaternary	Holocene	Alluvium	0–120	Silt, sand, gravel	Alluvial aquifer
	Pleistocene	Loess and glacial drift	0–11	Silty clay to silt	Not classified[b]
		Ferrelview Formation	0–22	Clay to silty clay	Glacial drift confining unit[c]
		Glacial till unit	0–47	Sandy and silty clay to clayey silt, with scattered rock fragments	Shallow aquifer
		Basal till unit	0–10	Sandy, clayey, silty gravel or gravelly silt	
Mississippian	Osagean	Residuum unit[d]	0–38	Clay, chert, silt; locally contains limestone fragments	
		Burlington-Keokuk Limestone	0–185	Limestone; silty, argillaceous, thickly bedded, cherty, fractured	Shallow aquifer
		Fern Glen Formation	0–67	Limestone; fine-grained, medium to thickly bedded, cherty	
	Kinderhookian	Chouteau Group	0–45 (+)	Dolomitic limestone; fine-grained, thinly to medium bedded	Upper confining
		Bachelor Formation	0–2	Sandstone; calcareous cement	
Devonian	Upper	Sulphur Springs Group			
		Bushberg Sandstone	0–20	Quartz sandstone; fine to medium-grained, friable	
		Glen Park Limestone	0–25	Calcareous siltstone, sandstone, uletic limestone, and hard carbonaceous shale	
Ordovician	Cincinnatian	Maquoketa Shale[e]	0–11	Calcareous or dolomitic shale; typically thinly laminated, silty with shaley limestone lenses	
	Champlainian	Kimmswick Limestone	41–104	Limestone; coarsely crystalline, medium to thick bedded, cherty near base	Middle aquifer
		Decorah Group	25–36	Shale with thin interbeds of very finely crystalline limestone	Confining unit

TABLE 1.1 (Cont.)

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Characteristics	Hydrostratigraphic Unit[a]
Ordovician (Cont.)	Champlainian (Cont.)	Plattin Limestone	70–125	Limestone; finely crystalline, thinly bedded	Lower confining unit
		Joachim Dolomite	80–105	Dolostone; thin to thickly bedded, grades into siltstone, shales common	
		St. Peter Sandstone	120–150	Quartz sandstone; fine- to medium-grained, massively bedded	Deep aquifer
	Canadian	Powell Dolomite	50–60	Dolostone; fine to medium crystalline, minor chert and shale	
		Cotter Dolomite	200–250	Argillaceous, cherty dolomite; fine to medium crystalline; interbedded with shale	
		Jefferson City Dolomite	160–180	Dolomite; fine to medium crystalline	
		Roubidoux Formation	150–170	Dolomitic sandstone	
		Gasconade Dolomite	–[f]	Cherty dolomite	
Cambrian	Upper	Eminence Dolomite	–[f]	Dolomite; medium to coarsely crystalline, medium-bedded to massive	
		Potosi Dolomite	–[f]	Dolomite; fine to medium crystalline, thick bedded to massive; drusy quartz common	

[a] When no hydrostratigraphic unit is listed, the unit is the same as for the preceding entry.

[b] These units are saturated in some places at the WSCP and the WSOW.

[c] A confining unit only where the base of the unit is below the potentiometric of the shallow aquifer, mainly in the August A. Busch Memorial Conservation Area.

[d] Residuum consists of the residual material from weathering of the uppermost bedrock formation and possibly younger rocks. The uppermost bedrock formation in most places is the Burlington-Keokuk Limestone.

[e] Identified in monitoring well MWGS-2.

[f] Insufficient data to estimate thickness.

Sources: Data from Whitfield et al. (1989); DOE (1992b); Kleeschulte and Imes (1994); and Mugel (1997).

weathered unit (MK-Ferguson Company and Jacobs Engineering Group 1990b). On the basis of subsurface data obtained at the WSCP and WSOW, this unit ranges in thickness from 0 to 34 m (0 to 113 ft) (Mugel 1994). Field data from borehole packer testing of the saturated bedrock also indicate a decrease in hydraulic conductivity with depth, which is attributed to decreased weathering and related solution activity.

1.1.2.2 Hydrogeology

The three regional bedrock aquifer systems present in the Weldon Spring area include a shallow unconfined aquifer (although it may be confined in some local areas), a confined middle aquifer, and a deep confined aquifer (Table 1.1). These systems are separated by confining units made up of limestone, dolomite, sandstone, and shale formations (Kleeschulte and Imes 1994). Regionally, the shallow bedrock aquifer primarily consists of saturated rocks of the Burlington-Keokuk Limestone and Fern Glen Formation; the middle aquifer is composed of the Kimmswick Limestone. The deep bedrock aquifer system consists of Ordovician and Upper Cambrian saturated rocks, which include formations from the top of the St. Peter Sandstone down through the bottom of the Potosi Dolomite (Kleeschulte and Emmett 1987). Groundwater that is used as a drinking water supply in the area is primarily taken from the deep aquifer and from an alluvial aquifer near the Missouri River; however, in St. Charles County, the shallow and middle aquifers are also used, primarily for rural domestic water supply (Kleeschulte 1991).

The groundwater system of primary interest in the Weldon Spring area is the shallow bedrock aquifer, which consists of a series of hydraulically connected limestones and, in some locations, the overlying saturated residuum or glacial drift. The shallow aquifer includes the Burlington-Keokuk Limestone, which is the uppermost bedrock formation beneath the WSCP and most of the WSOW. The principal recharge to this shallow groundwater system is through infiltration of precipitation from the overburden or from losing streams. The shallow groundwater system is the focus of these operable units because of impacts from previous activities.

The shallow aquifer is primarily unconfined, although it may be confined in a few local areas where the groundwater extends into the overlying glacial drift. The water table elevation fluctuates seasonally and with precipitation, but remains within the upper bedrock, residuum, or glacial drift. An east-west trending groundwater divide, which coincides with the topographic high,

has been identified that results in two distinct drainage systems (Missouri Department of Natural Resources 1991; DOE 1992b; IT Corporation 1992a; Kleeschulte and Imes 1994).

At the WSOW, shallow groundwater north of the divide flows to the north, and shallow groundwater south of the divide flows to the south following natural gradients (DOE and DA 1998b; Figure 1.5). In the northeastern portion of the WSTA and northwest of the WSCP, a subsurface conduit system transports water rapidly to Burgermeister Spring. The presence of the conduit system (a subsurface pathway in which water flows at a high velocity and does not obey Darcy's law [White 1988]) is inferred by a groundwater trough in the contoured water table surface south of Burgermeister Spring, which extends into the northern portion of the chemical plant and the northeastern portion of the ordnance works area. Water-tracing tests provide additional evidence for the presence of a conduit system in this area (Missouri Department of Natural Resources 1991; Price 1991; DOE and DA 1998b). These features are located north and south of the WSTA.

The Burgermeister Spring area appears to be a major groundwater discharge area for drainage from the eastern and central portions of the WSTA and the northern and western portion of the WSCP. Groundwater in the northwestern portion of the WSTA flows to two western valleys (i.e., the 6500 drainage and a small drainage to the west of the 6500 drainage) (IT Corporation 1993b). Groundwater flow in the southern portion of the WSOW is contained within its surface drainage (i.e., does not cross into other drainages) and discharges at numerous small springs (Figure 1.6).

At the WSCP, groundwater to the north of the divide flows north and west toward Burgermeister Spring and eventually toward Dardenne Creek, a tributary of the Mississippi River. At the chemical plant, groundwater to the south of the divide flows south to southeast toward the Missouri River, primarily through the 5300 drainage. Because the Southeast Drainage is a losing stream in portions of its upper reaches, mixing between groundwater and surface water runoff can occur.

1.1.2.3 Surface Water

The WSOW and the WSCP are located on an east-west drainage divide between the Missouri and Mississippi watersheds (Missouri Department of Natural Resources 1991; IT Corporation 1992b) (Figure 1.6). At the western part of the WSOW, surface drainage to the south

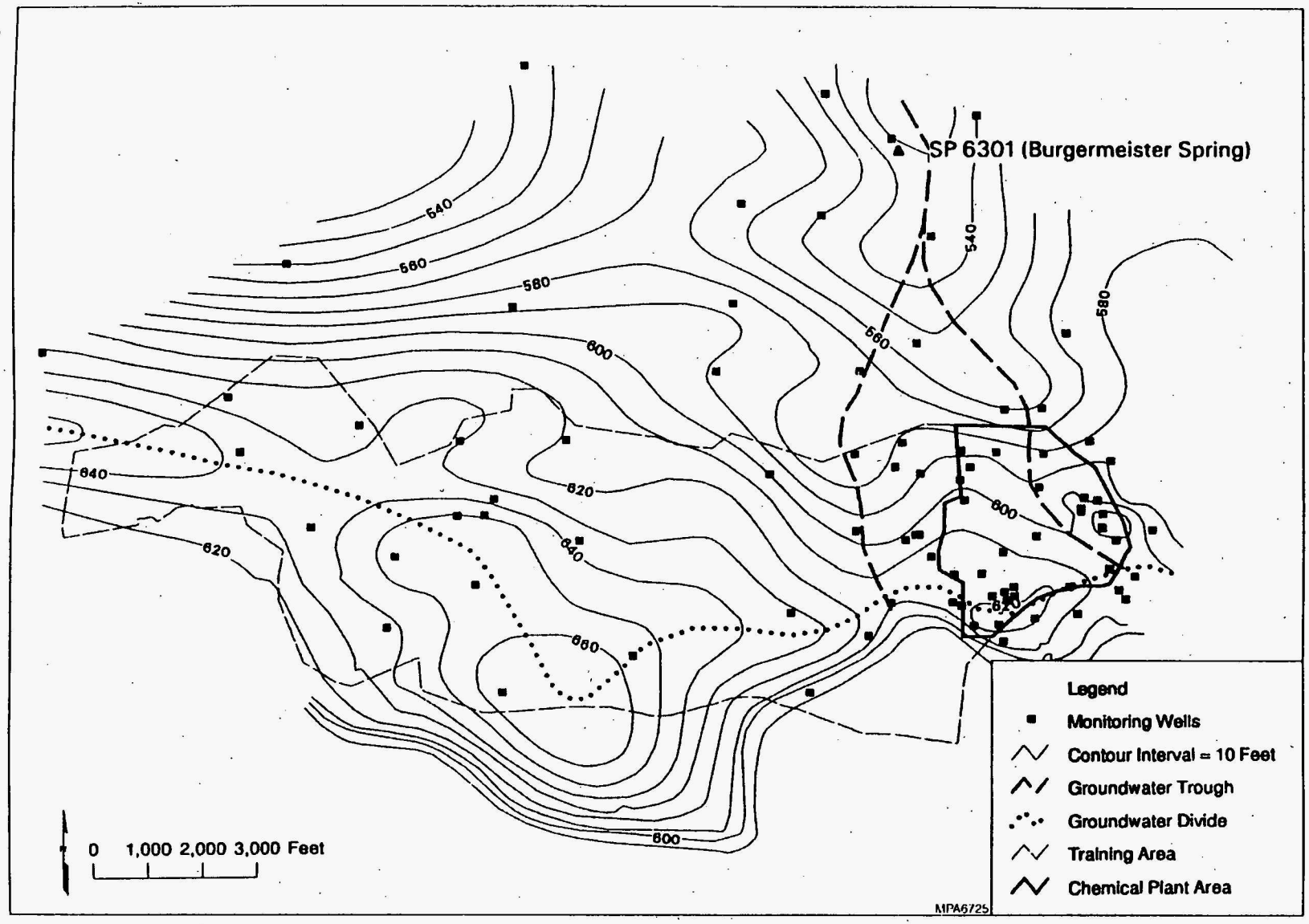

FIGURE 1.5 Hydraulic Head Distribution in the Shallow Groundwater — July 1995

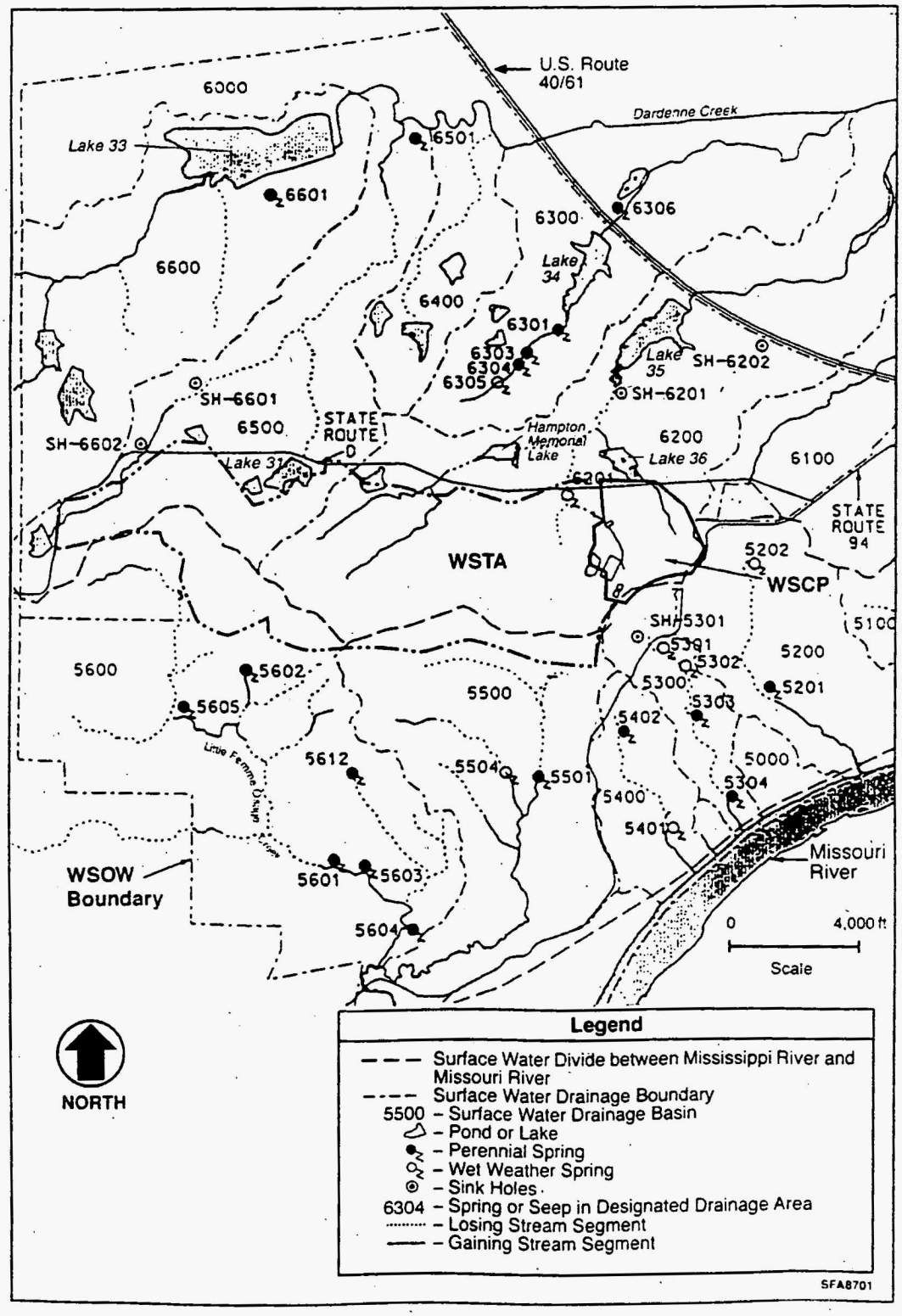

FIGURE 1.6 Gaining and Losing Stream Segments and Associated Springs and Seeps at the WSOW

of the divide flows to Little Femme Osage Creek and its tributaries, which ultimately discharge into the Missouri River. At the eastern part of the WSOW, surface drainage to the south of the divide flows toward and discharges to the Missouri River. Surface drainage to the north of the divide flows toward Dardenne Creek and its tributaries. Schote Creek, the largest of the tributaries, drains a major portion of the training area and the WSCP. Dardenne Creek flows easterly and ultimately into the Mississippi River (IT Corporation 1992a; DOE 1992b). Because of the presence of the surface drainage divide, surface water from the WSCP flows to the adjacent WSOW.

1.1.2.4 Biotic Resources

The principal surface water feature of relevance to these operable units is Burgermeister Spring. This spring is located in the former WSOW north of the WSCP in upland forest with a relatively dense understory. Tree species present in this area include red oak, persimmon, Kentucky coffee tree, and cottonwood. Ground cover immediately around the spring is dominated by periwinkle, whereas the shrubby understory is predominantly honeysuckle. At Burgermeister Spring, groundwater discharges into a square concrete enclosure about 1.5 m (4.9 ft) on each side and about 0.5 m (1.6 ft) high. Springwater within the enclosure flows through a crack in the concrete wall into a small natural stream channel (about 1 m [3.2 ft] wide). A small concrete weir is located about 15 m (50 ft) downstream of the spring and creates a small pool with a sand/silt bottom (about 2 m × 3 m [7 ft × 9 ft] and about 0.3 m [1 ft] deep). Below the weir, the stream flows over a sand, gravel, and cobble substrate for about 15 m (50 ft) and then joins a larger stream that flows into Lake 34 about 1 km (0.6 mi) downstream of the spring.

No fish occur above the weir, which effectively serves as a barrier to the upstream passage of fish. The fish community of Burgermeister Spring below the weir is typical of Midwestern headwater streams; reported species include the orange throat darter, green sunfish, brook silverside, and redfin shiner. The larger stream that receives inflow from the spring and discharges to Lake 34 supports a more diverse fish fauna, including species common to Lake 34 that may use the stream as spawning and nursery habitat. Fish using the stream may include the black and white crappie, green sunfish, bluegill, largemouth bass, carp, and black bullhead.

1.1.2.5 Land Use

The 700-ha (1,655-acre) WSTA is adjacent to the WSCP. Both areas are fenced, and access by the general public is restricted. Portions of the training area that are not contaminated are currently used for field training and outdoor maneuvers by the U.S. Army Reserve, the Missouri Army National Guard, and other military and police units. An estimated 3,300 local Army reservists and 3,400 other reserve troops use the training area each year (Daubel 1992). The Army intends to continue and even expand use of the WSTA area for training activities in the future.

A large portion of the WSOW has been converted into conservation areas (Figure 1.2). The 2,828-ha (6,987-acre) August A. Busch Memorial Conservation Area and the 2,977-ha (7,356-acre) Weldon Spring Conservation Area are managed by the Missouri Department of Conservation and are open throughout the year for recreational use. These areas receive an estimated 1,200,000 visitors each year (Crigler 1992).

A state highway maintenance facility is located just east of the WSCP. The facility employs nine full-time staff and one mechanic (Sizemore 1991). The former staff housing complex for the former WSOW, located southeast of the intersection of State Route 94 and U.S. Route 40/61, is currently a private housing development known as Weldon Spring Heights, which has a population of about 80. Francis Howell High School is located about 1 km (0.6 mi) east of the WSCP. The school employs about 175 faculty and staff (including employees at the Francis Howell Administration Annex) and is attended by about 1,930 students (Meyer 1993).

County zoning requirements for future housing developments in the area around the WSCP and the WSOW indicate that municipal wastes would be the source of drinking water for potential future residents in the area. Housing developments or subdivisions are generally platted for home lots of no more than 0.4 ha (1 acre) in size that must be provided with municipal water. During the last two years, only one building permit was issued in the City of Weldon Spring for a private residence with an individual well. During the past 10 years, no building permits have been issued in the City of O'Fallon for residences with private wells for water supply. Also, for the period between 1993 and 1996, only two wells were installed (at less than 91 m [300 ft] deep) downgradient of the WSCP and the WSOW sites, out of approximately 2,200 new homes started (Tunnicliff 1997).

These housing trends support the belief that use of site groundwater for residential purposes might be limited.

1.2 NATURE AND EXTENT OF CONTAMINATION

The nature and extent of contamination within the groundwater system for the WSCP and the WSOW were evaluated on the basis of groundwater and spring data collected under DOE and DA environmental monitoring programs from 1987 through 1995 and a joint sampling effort conducted in 1995. Data for groundwater at the WSCP and the WSOW were combined and evaluated together because the groundwater system is continuous beneath both areas.

1.2.1 Groundwater

To facilitate the interpretation of data regarding the vertical distribution of contaminants in groundwater, data were grouped into four stratigraphic units: the overburden, weathered Burlington-Keokuk, unweathered Burlington-Keokuk, and deeper units. The results of the data evaluation indicated that contaminants evaluated at greater than background levels include nitrate, uranium, chloride, sulfate, lithium, and molybdenum. Organic compounds that include trichloroethylene (TCE), 1,2-dichloroethylene (1,2-DCE), and nitroaromatic compounds have also been detected. However, this discussion will focus on the set of contaminants that are considered to be primary contributors to potential site risk.

The extent of uranium and nitrate contamination in groundwater is primarily limited to the WSCP and nearby vicinity. Higher concentrations have typically been measured near the raffinate pits, predominantly in the overburden and weathered units of the aquifer. Data from the joint sampling effort conducted in 1995 indicated concentrations as high as 900 mg/L for nitrate and 60 pCi/L for uranium. The maximum data point for uranium was reported for MW-4024, which was installed just before collection of this data point. It is suspected that bentonite grout used for well installation contributed to the uranium high concentrations (DOE and DA 1998b). A more recent data point reported for this well (July 1997) was 6.7 pCi/L. Elevated levels of uranium were also detected in shallow groundwater in the Southeast Drainage; in-situ samples ranged in concentration from 2.1 to 160 pCi/L. However, sampling of a new well installed near the Southeast Drainage area in May 1997, has shown no detected concentrations of uranium (i.e., < 0.68 pCi/L).

Nitroaromatic compounds occur sporadically at low levels across the groundwater system; higher levels have generally been detected in the overburden and weathered units of the aquifer. The primary nitroaromatic compounds detected include 2,4-dinitrotoluene (2,4-DNT), 2,6-dinitrotoluene (2,6-DNT), 1,3,5-trinitrobenzene (1,3,5-TNB), 2,4,6-trinitrotoluene (2,4,6-TNT), and the amino-DNT compounds (2-amino-4,6-dinitrotoluene [2-amino-4,6-DNT] and 4-amino-2,6-dinitrotoluene (4-amino-2,6-DNT]). The 1995 joint sampling data indicated maximum concentrations ranging from 8 to 100 µg/L for these compounds.

Groundwater contamination of TCE and 1,2-DCE is localized at the WSCP, primarily in the vicinity of the raffinate pits. The areal extent of contamination extends from east of raffinate pit 3 to the south and southeast of raffinate pit 4, just beyond the adjacent boundary with the WSTA. Most of the contamination occurs in the weathered portion of the aquifer. TCE has been detected in one unweathered well (MW-3025); however, after this well was retrofitted to fix a leaking seal, no TCE was detected. Concentrations in groundwater have ranged from 1 to 9,000 µg/L for TCE and from 1 to 39 µg/L for 1,2-DCE. The most recent data collected (as of December 1997) indicate TCE concentrations ranging from 1 to 1,300 µg/L and 1,2-DCE concentrations ranging from 1 to 29 µg/L.

The distribution of contamination for selected contaminants (i.e., TCE and 1,2-DCE, nitrate, 2,4-DNT, 2,4,6-TNT, 1,3-DNB, and uranium) is illustrated in Figures 1.7 through 1.12. The 95% upper confidence limit (UCL) of the arithmetic average values for each well are shown in the figures for different stratigraphic groupings (i.e., overburden and weathered Burlington-Keokuk Limestone grouping; and unweathered Burlington-Keokuk and deeper units grouping). For naturally occurring constituents (i.e., uranium and nitrate), only those wells that exceed the statistically derived background are shown. For uranium and nitrate, the UCL values for each well are calculated on the basis of more recent data only (1995–1997), since these data are believed to be a more accurate representation of current contamination levels. Wells that are considered to be impacted by uranium processing activities are designated in the distribution maps; these wells were determined on the basis of data evaluation, existing or previous source areas, and groundwater flow. The distribution maps for nitroaromatic compounds, TCE, and 1,2-DCE show all the locations where these compounds were detected. The UCL values for nitroaromatic compounds were calculated on the basis of all data collected since 1987. The UCL values for TCE and 1,2-DCE were calculated on

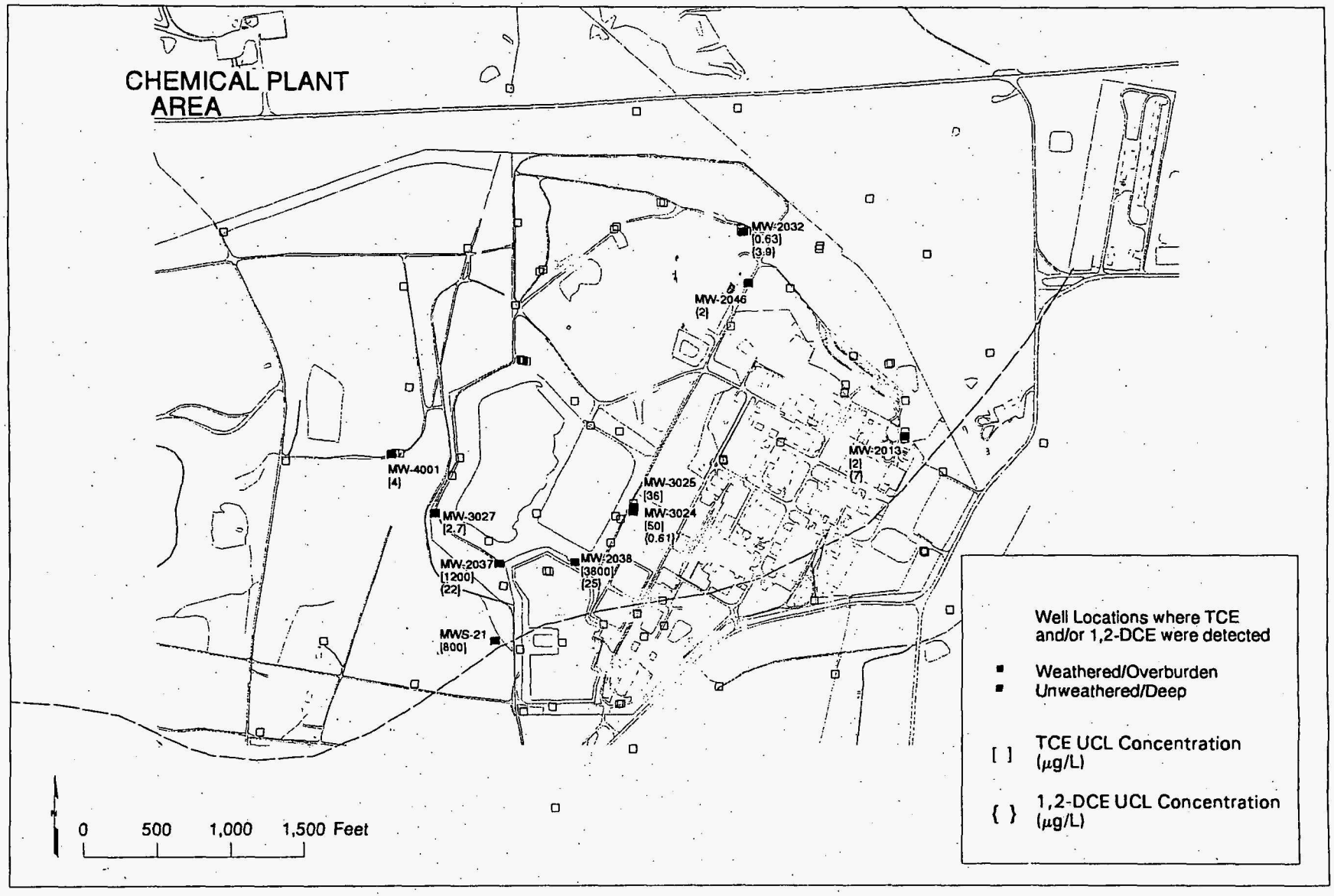

FIGURE 1.7 Distribution of TCE and 1,2-DCE at the WSCP and the WSOW

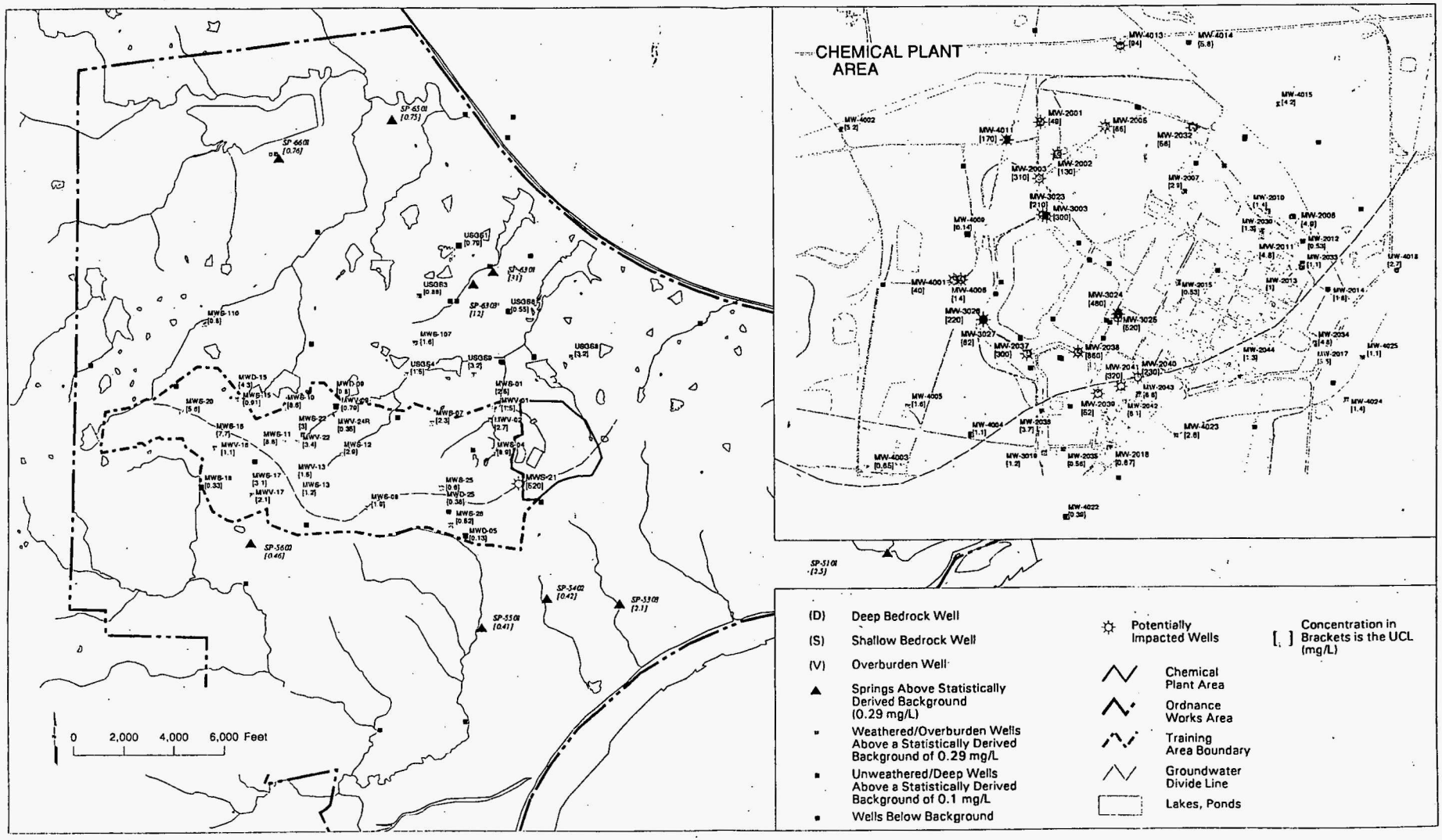

FIGURE 1.8 Distribution of Nitrate at the WSCP and the WSOW

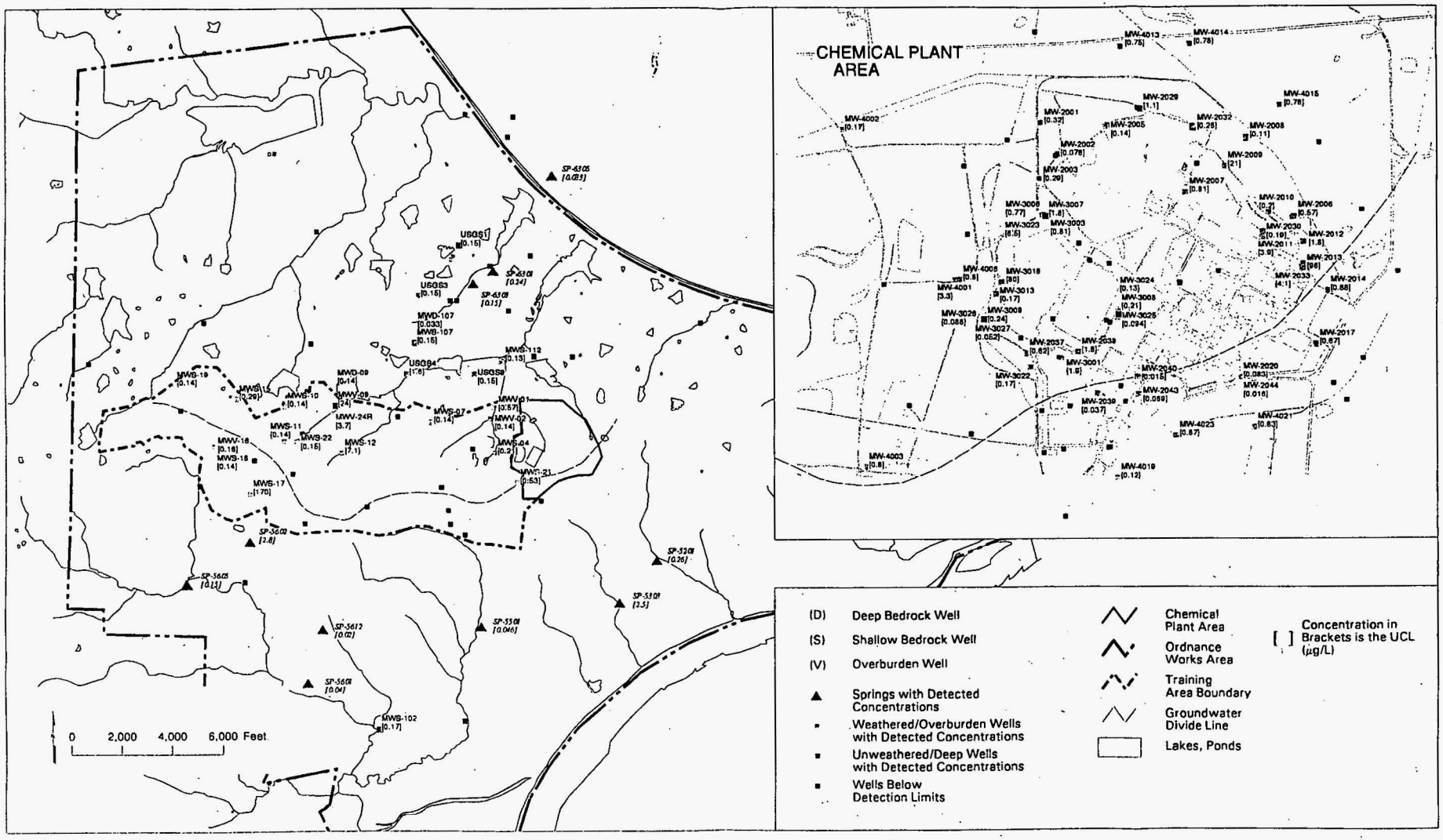

FIGURE 1.9 Distribution of 2,4-DNT at the WSCP and the WSOW

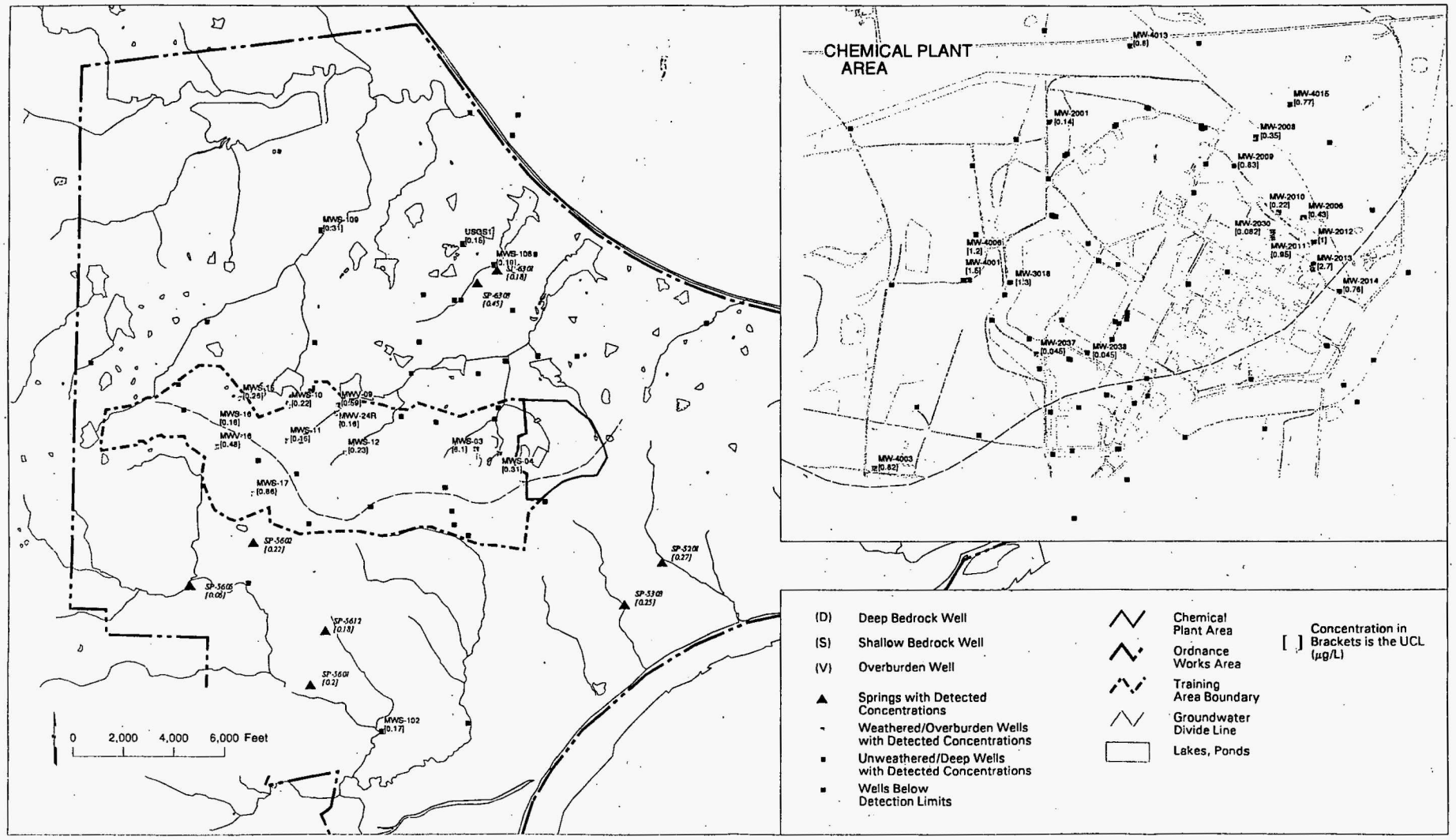

FIGURE 1.11 Distribution of 1,3-DNB at the WSCP and the WSOW

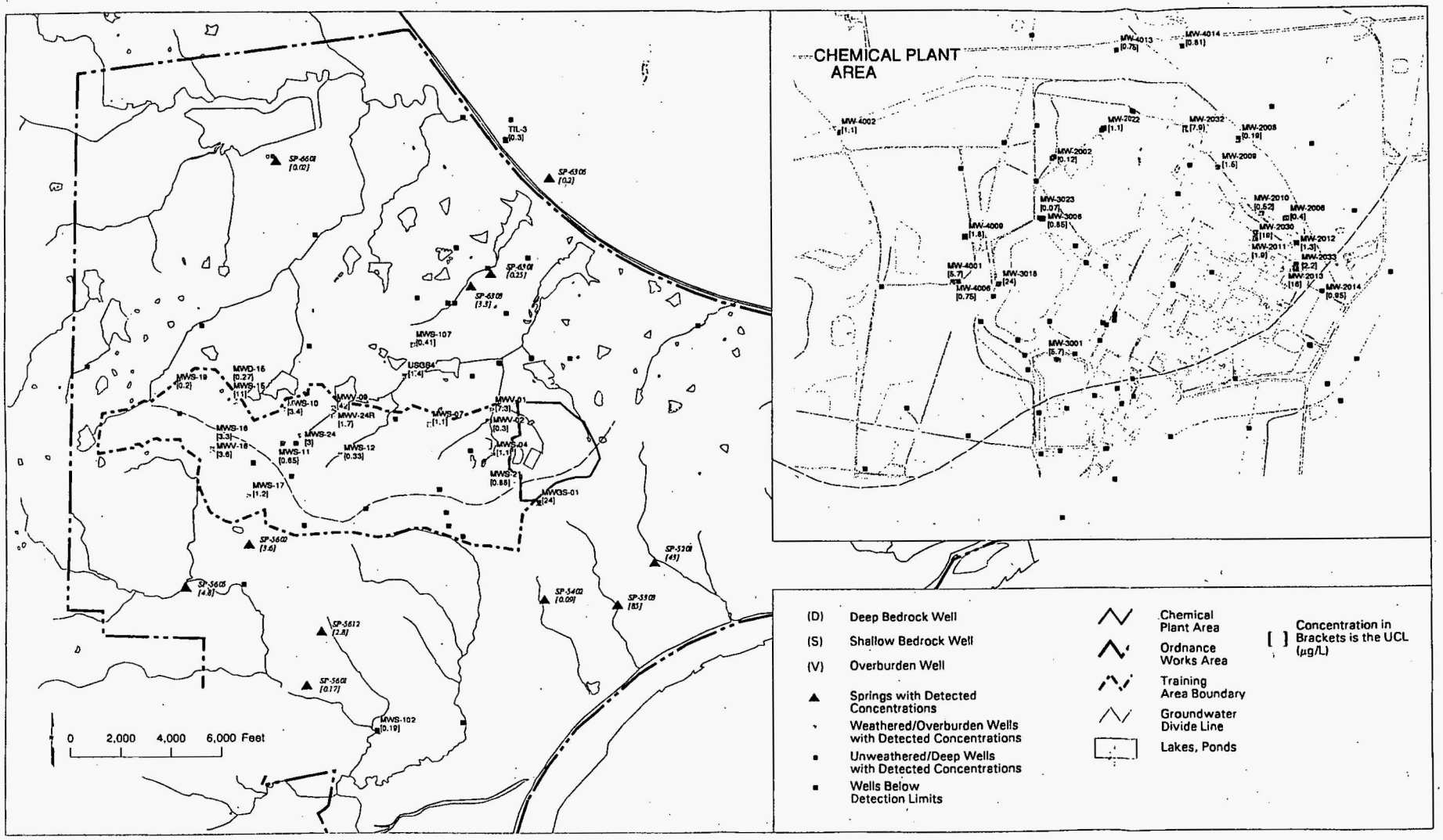

FIGURE 1.10 Distribution of 2,4,6-TNT at the WSCP and the WSOW

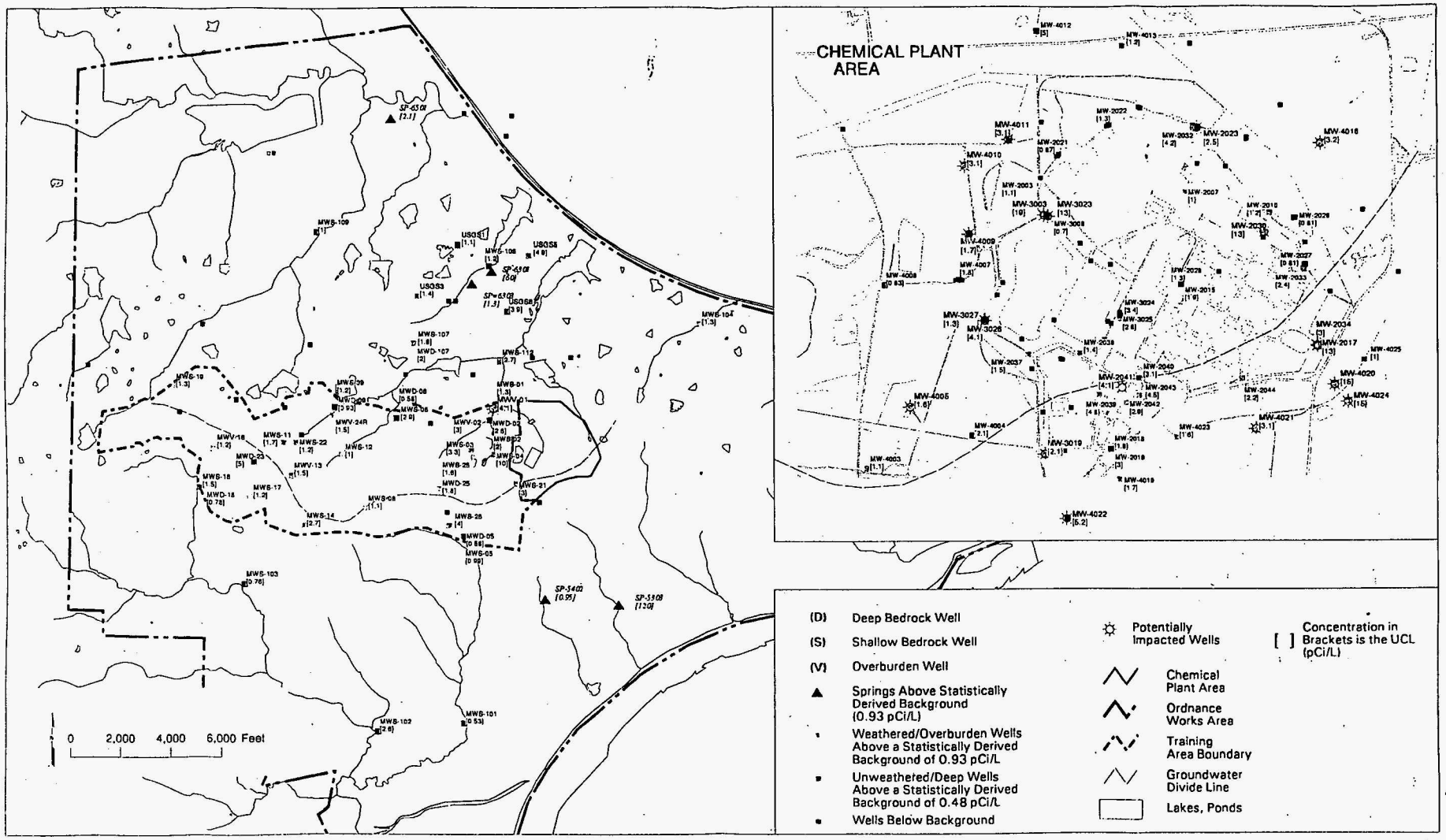

FIGURE 1.12 Distribution of Uranium at the WSCP and the WSOW

the basis of data collected since 1996. Distribution maps for the other site contaminants are presented in the RI (DOE and DA 1998b).

1.2.2 Springwater

The primary contaminants detected in springwater include uranium, nitrate, sulfate, and nitroaromatic compounds. Elevated levels of uranium and nitrate have been routinely detected at Burgermeister Spring (6300 drainage). Nitrate concentrations at this location have historically ranged from 0.5 to 10,000 mg/L; data collected since 1995 indicated a range of 3.8 to 47 mg/L. The 1995 joint sampling indicated a maximum concentration of 91 pCi/L. Elevated uranium levels have also been routinely detected in the Southeast Drainage (5300 drainage). Elevated sulfate levels, ranging from 3.2 to 86 mg/L, were found in springs in the 5100, 5200, 5300, and 6300 drainages.

Nitroaromatic compounds have been detected in springs at low levels from most of the drainages in the former WSOW, except for the 5100 drainage. The highest levels of 2,4,6-TNT occurred in Spring 5201 (downstream of Burning Ground 1) and in the Southeast Drainage, with concentrations of 120 and 280 µg/L, respectively. Concentrations of other nitroaromatic compounds detected throughout the area have ranged from 0.02 to 24 µg/L.

Other naturally occurring constituents detected at above background levels include chloride, antimony, cadmium, lithium, manganese, mercury, molybdenum, and silver. Four springs were also sampled for volatile organic compounds (VOCs), beginning in August 1996. The springs included Burgermeister Spring, Spring-6303, and two springs in the Southeast Drainage. No VOCs were detected in the Southeast Drainage. Low levels of TCE were detected in the 6300 drainage (i.e., less than 1.72 µg/L).

1.3 SUMMARY OF POTENTIAL RISKS

Potential impacts to human health and the environment from groundwater and springwater contamination were evaluated for the WSCP and the WSOW if no cleanup was undertaken for these media. Current and likely future land uses were incorporated into assumptions for these risk estimates.

1.3.1 Human Health Assessment

Potential carcinogenic risks for both radiological and chemical exposures were assessed in terms of the increased probability that an individual would develop cancer over a lifetime. The EPA has indicated that for known or suspected carcinogens, the acceptable exposure levels for members of the general public at sites on the NPL are generally concentrations that represent an excess upper-bound lifetime cancer risk to an individual of between 1×10^{-6} and 1×10^{-4} (EPA 1989b). This range is used as a point of reference for discussing the results of the carcinogenic risk assessment for the GWOUs at the WSCP and WSOW.

Potential health effects other than cancer from exposure to chemical contaminants were also assessed. The quantitative measures of noncarcinogenic health effects are the hazard quotient and hazard index. The EPA has defined a hazard index of greater than 1 as the level of concern for noncarcinogenic health effects.

Contaminants identified in the RI as site-related contaminants were included in the risk calculations. The evaluations performed as part of the RI included the identification of site-related contaminants, which was based on an understanding of the processes that occurred at the sites and on evaluation of approximately 10 years of data; for naturally occurring contaminants (i.e., metals and inorganic anions), these data were also compared with background values. Hazard indices and carcinogenic risks from contaminants identified as site-related contaminants were estimated by using either the maximum concentration or the 95% UCL of the arithmetic average of the data set collected for each contaminant.

1.3.1.1 Exposure Scenarios

The most likely receptor under current land use was assumed to be a recreational visitor who might be exposed to contaminated discharge water at one of the springs. On the basis of current land use information, the analysis also assumed that there would be no current access and use of the groundwater (see Section 1.1.2.5). Army reservists and a full-time site caretaker of the WSOW were also considered as potential receptors; however, these scenarios were not evaluated. There are no potential pathways of exposure for the reservist because no active springs occur in the WSTA, and municipal water is available at a tap. Similarly, the potential for the site caretaker to come in contact with the contaminated groundwater and springs is unlikely because of the availability of municipal

water. The potential risk to a reservist who might venture outside the fenced training area and drink springwater would be covered by the calculations performed for the recreational visitor. It was considered reasonable for reservists to train at the WSTA two to three weekends (about six days) per year. If these same reservists also spent their yearly retreat training of two weeks at the WSTA, the frequency of exposure would extend to about 20 days, which is the same as the exposure frequency assumed in the risk calculations for a recreational visitor.

Under future land use, the most likely receptor would also be a recreational visitor. It is unlikely that the shallow aquifer beneath the WSCP and the WSOW would be used by a future resident on the basis of current and foreseeable future land use. The Army intends to continue using the WSTA for training activities in the future. The WSCP is currently being remediated; all site waste will ultimately be disposed of in an engineered disposal cell constructed on-site. The size of the cell is estimated to encompass approximately one-third of the WSCP.

In addition, a large portion of the former WSOW has been converted into conservation areas. The August A. Busch Memorial Conservation Area and the Weldon Spring Conservation Area are managed by the Missouri Department of Conservation and are open throughout the year for recreational use. These areas are extensively used, as indicated by the estimated 1,200,000 visitors each year (Crigler 1992).

Because of the low transmissivity and low yield of the upper part of the shallow aquifer, a future resident would likely screen a private well in the deeper, more productive aquifers. Also, the well would be open to a larger portion of the shallow aquifer (rather than only the upper weathered unit of the Burlington-Keokuk) because of the 24-m (80-ft) casing requirement.

Nevertheless, as a means of providing information representing the upper-bound risk to human health from groundwater contamination, risk calculations were performed for the hypothetical future resident. Separate calculations to estimate risk for recreational use of the groundwater were not performed because one can infer potential risk to a recreational user from the calculations for the residential scenario. By using the standard exposure parameter assumptions recommended by the EPA for a recreational visitor (i.e., assuming the recreational visitor could somehow access the groundwater 20 times per year for 30 years and ingest approximately 400 mL each visit), the potential risk and hazard index would be approximately one-hundredth of those for a resident.

Pathways evaluated for the resident included ingestion and dermal contact through showering. An additional pathway of inhalation while showering was evaluated only for TCE.

1.3.1.2 Risk Characterization

Neither carcinogenic risk nor systemic toxicity is indicated for the recreational visitor incidentally ingesting springwater at the 15 springs evaluated; these results are expected to be representative of all springs located in the area covered by the GWOUs. The radiological risk estimates range from 4×10^{-9} to 3×10^{-6}. These values are low and well within the acceptable risk range of 1×10^{-6} to 1×10^{-4} recommended by the EPA (1989b). The chemical risk estimates are similarly low and range from 3×10^{-10} to 6×10^{-7}. The hazard indices estimated for the recreational visitor at the springs range from 0.001 to 0.4.

The well-by-well calculations for the hypothetical future resident scenario indicate that of the 155 wells evaluated, chemical risks would be greater than 1×10^{-4} for seven wells. The chemical risk estimates for the 155 wells range from 1×10^{-7} to 3×10^{-3}. The upper end of this range is attributable to TCE detected at well MW-2038, which is located north of the groundwater divide. The chemical risk estimates and primary risk contributors for the other six wells are as follows: 2×10^{-4} at MWV-09 and MWS-12 due to nitroaromatic compounds; 1×10^{-4} at MWS-17 due to nitroaromatic compounds; 1×10^{-4} at MW-2030 due to nitroaromatic compounds; 4×10^{-4} at MW-2037 due to TCE; and 1×10^{-4} at MWS-21 due to TCE. The TCE-contaminated wells are near the raffinate pits and are completed in the weathered portion of the shallow aquifer. On the basis of estimates for the residential scenario, the chemical risk estimates for a recreational visitor would be within the acceptable risk range (i.e., at less than 1×10^{-9} to 3×10^{-5}). The radiological risk estimates for the residential scenario range from 7×10^{-8} to 7×10^{-5}, all within the EPA's acceptable risk range; the potential radiological risks for the recreational visitor would be in the range of 7×10^{-10} to 7×10^{-7}.

The estimated hazard indices for the 155 wells based on the residential scenario range from 0.01 to 40. The hazard indices for 43 of the 155 wells evaluated are greater than 1. Of the 43, hazard indices for 27 wells are attributable to nitroaromatic compounds. Elevated nitrates occur mostly in the WSCP 2000- and 3000-series wells; 15 hazard indices that are greater than 1 are attributable to nitrate concentrations in these wells. Uranium concentrations in another well (MW-4024)

contributed to a hazard quotient of 0.84 out of a hazard index of 1. The hazard indices for these wells based on a recreational scenario would be approximately one-hundredth of those estimated for the residential scenario.

In summary, the following contaminants can be identified as contaminants of concern (COCs) on the basis of their contributions to carcinogenic estimates: TCE and the nitroaromatic compounds 2,4,6-TNT, 2,4-DNT, and 2,6-DNT. In addition, nitrates and nitroaromatic compounds (primarily 1,3,5-TNB, 2-amino-4,6-DNT, and 4-amino-2,6-DNT) are considered COCs relative to their contributions to the hazard indices. Uranium is considered a COC only with regard to its possible transport to the springs. Higher uranium concentrations have been detected in Burgermeister Spring samples than in groundwater samples. Groundwater concentrations of uranium have been determined to result in potential radiological risk within the acceptable risk range.

1.3.2 Ecological Assessment

1.3.2.1 Methodology

The ecological risk assessment for the GWOUs employed a number of approaches for evaluating risks to ecological resources using springs at the WSCP and the WSOW. Risks to aquatic biota were evaluated with biotic surveys, tissue analyses of fish and macroinvertebrates, media toxicity testing, and comparison of media concentrations to ecological benchmark ("safe") media concentrations. Risks to terrestrial biota were evaluated by modeling contaminant uptake and comparing the predicted doses to species-specific benchmark doses. Contaminant data used in the assessment included the same surface water data used in the human health risk assessment, as well as sediment data collected specifically for the ecological risk assessment at Burgermeister Spring and selected downstream locations.

Biotic surveys for aquatic invertebrates, fish, and amphibians were conducted at Burgermeister Spring and its downstream drainage to determine the status of the biotic communities currently exposed to contaminants in surface water and sediment at the spring. Tissues were also analyzed to evaluate contaminant bioconcentration by aquatic biota. Toxicity testing of surface water and sediment from the spring and downstream locations included acute and chronic toxicity testing of aquatic invertebrates, fish, and amphibians. These tests determined whether current contaminant

concentrations in the surface water and sediment are toxic to aquatic biota. Contaminant uptake from the ingestion of surface water was modeled for two terrestrial receptor species, the white-tailed deer and the American robin. The uptake modeling employed species-specific exposure factors; the exposure point concentrations were the maximum reported contaminant concentrations in surface water from springs at the WSCP and WSOW.

1.3.2.2 Results And Conclusions

The results of surveys of macroinvertebrates, fish, and amphibians that inhabit the Burgermeister Spring drainage indicated no evidence of adverse effects to these aquatic biota. The spring was determined to contain generally good aquatic habitat, and the species present are typical of those found in similar habitats throughout the Midwest. Although the fish community was limited in diversity and the macroinvertebrate community was categorized as slightly impaired, the communities are likely affected by the physical nature of the spring and its drainage rather than contaminant levels. Flow in the uppermost portion of Burgermeister Spring is maintained by groundwater discharge at the spring. Under low-flow conditions, as commonly occur in the summer, the stream drainage below the spring becomes intermittent and portions of the habitat become dry. Surveys of amphibians found a community typical of similar habitats in the Midwest.

The results of toxicity testing indicate the potential for some toxicity to fish and invertebrates from surface water and sediment in Burgermeister Spring proper, although the magnitude of the toxicity is low to moderate. Surface water and sediment toxicities were also measured at some locations downstream of the spring, but no clear toxicity gradient was evident extending downstream from the spring. However, the presence of apparently unaffected macroinvertebrate, fish, and amphibian communities in the drainage at locations where media toxicity was detected suggests that local populations are tolerant of (or have adapted to) the contaminant levels present in surface water and sediment in the Burgermeister Spring drainage. Tissue analyses revealed relatively low levels of contaminant bioconcentration, all below levels of concern.

Modeling of contaminant uptake by the white-tailed deer and American robin drinking from Burgermeister Spring (but using maximum contaminant concentrations reported from all springs) predicted very low levels of contaminant uptake by these species. Risk estimates for terrestrial biota

based on the modeled contaminant doses indicate no risks to terrestrial biota drinking from Burgermeister Spring or other springs in the area.

Risk estimates for aquatic biota based on media concentrations indicate that surface water concentrations of iron, manganese, mercury, uranium, 1,3,5-TNB, and 2,4,6-TNT, and sediment concentrations of arsenic, lead, and silver might pose low to moderate risks to aquatic biota. However, the aquatic community in Burgermeister Spring is typical of similar habitats elsewhere in the Midwest and does not appear to be adversely affected by contaminant concentrations at this time. Few of the other springs in the area provide suitable habitat and, at best, naturally support only very limited aquatic communities.

On the basis of the results of biotic surveys, media toxicity testing, tissue analyses, media-based risk calculations, and contaminant uptake modeling, current contaminant levels in surface water and sediment in area springs are considered to pose little or no risk to aquatic or terrestrial biota of the Weldon Spring area. Risk calculations indicated a potential for low to moderate risks to aquatic biota from some contaminants in springs, and surface water and sediment toxicities were detected for Burgermeister Spring. However, biotic surveys of Burgermeister Spring and downstream habitats found no evidence that aquatic biota inhabiting this spring are being adversely impacted; few other springs naturally provide sufficient permanent habitat to support more than only very limited aquatic communities. Uptake modeling indicates no risks to terrestrial wildlife using the area springs for drinking water.

1.4 OBJECTIVE OF THE FEASIBILITY STUDY

The objective of this feasibility study is to evaluate potential options for addressing groundwater contamination at the WSCP and the WSOW. This FS provides sufficient information to support decisions in accordance with the integrated environmental compliance processes for the WSSRAP and for the remedial action project at the WSOW, which includes the WSTA.

Water at surface springs located at the WSCP and the WSOW was also evaluated as part of the RI/BRA. Contaminant concentrations are estimated to result in human health risk within or lower than the acceptable risk range recommended by the EPA (i.e., 1×10^{-6} to 1×10^{-4}). The results of the ecological assessment also did not indicate the need for remediation at the springs. The likely future land use is considered to be similar to the current recreational land use, for which groundwater

is not used. Estimates for groundwater risk based on the assumption of occasional use by a recreational visitor if access was available indicate that risk levels would be within the EPA's acceptable risk range and below a hazard index of 1. However, risk estimates based on the conservative assumption of residential land use indicate that exposure to contaminated groundwater at a few wells would result in a potential risk of greater than 1×10^{-4} and a hazard index of 1. Because it is expected that source removals planned and/or currently ongoing at both the WSCP and WSOW would lead to a decrease in contaminant concentrations, options that allow for verification of decreasing concentrations were evaluated. The analysis for this FS also focused on the evaluation of applicable engineering options for removing or reducing groundwater contaminant concentrations to provide additional overall protection of human health and the environment.

1.5 DETERMINATION OF PRELIMINARY REMEDIATION GOALS FOR GROUNDWATER AT THE WSCP AND THE WSOW

On the basis of the results of evaluations presented in the BRA and RI (DOE and DA 1998a,b), the focus and primary objective of this FS is the identification of options that allow for verification of decreasing contaminant concentrations as the result of source removals and options that reduce or remove contaminant concentrations (i.e., TCE, nitrates, uranium, and nitroaromatic compounds in groundwater). Nitrate and TCE contamination are primarily of concern at the raffinate pits area at the WSCP. Nitroaromatic compounds have been identified as COCs in a few wells at both the WSCP and the WSOW. Although uranium concentrations in groundwater at the WSCP and at the WSOW are elevated over background, concentrations are generally low. Uranium concentrations are generally higher at the WSCP than those reported for the WSOW. Estimated risks from uranium, however, including those detected at the WSCP, are within the acceptable risk range (see Section 1.4).

Preliminary remediation goals (PRGs) for TCE, nitrates, nitroaromatic compounds (i.e., 2,4,6-TNT, 2,4-DNT, 2,6-DNT, 2-amino-4,6-DNT, 4-amino-2,6-DNT, nitrotoluenes, 1,3,5-TNB, 1,3-dinitrobenzene [1,3-DNB], and nitrobenzene), and uranium are identified in this FS as a basis for evaluating the effectiveness of the various technologies and alternatives being considered. In accordance with the National Oil and Hazardous Substances Contingency Plan ([NCP]; EPA 1990a), the PRGs are concentrations of contaminants for each exposure route that are

believed to provide adequate protection of human health and the environment on the basis of preliminary site information. They are initially based on applicable or relevant and appropriate requirements (ARARs) — for example, maximum contaminant levels (MCLs). For all classes of chemicals, the EPA uses ARARs, when available, to set remediation goals. When ARARs are not available or are not sufficiently protective, the EPA sets remediation goals for noncarcinogenic chemicals such that exposure presents no unacceptable risk of significant adverse effects to individuals on the basis of a comparison of exposures associated with reliable toxicity information such as EPA reference doses (RfDs). When ARARs do not exist for carcinogens, the EPA selects remedies resulting in a risk range of 1×10^{-4} to 1×10^{-6} incremental lifetime cancer risk. A detailed discussion and compilation of ARARs and to-be-considered (TBC) requirements is presented in Appendix A.

An MCL of 5 µg/L has been identified for TCE and an MCL of 10 mg/L for nitrates as nitrogen (nitrate-N). For nitroaromatic compounds, a concentration for 2,4,6-TNT has been set by the EPA as a drinking water health advisory. This value has been determined to be a TBC (see Appendix A). Missouri water quality standards may serve as ARARs for nitroaromatic compounds considered to be COCs for the GWOUs. Missouri water quality standards contain specific concentrations for 3 of 11 nitroaromatic compounds of concern — that is, nitrobenzene, 2,4-DNT, and 1,3-DNB (10 *Code of State Regulations* [CSR] 20-7.031(5)).

No federal or state MCL or maximum contaminant level goal (MCLG) exists for uranium. On July 18, 1991, the EPA published a proposed rule that set an MCL of 20 µg/L for uranium (EPA 1991). The proposed MCL corresponds to 14 pCi/L for the activity concentration ratio of uranium isotopes found in groundwater at the WSCP. In 1995, the EPA promulgated a final rule for groundwater standards for remedial actions at inactive uranium processing sites (EPA 1995a). That final rule sets a concentration limit for uranium of 30 pCi/L to provide an adequate margin of safety against both carcinogenic and systemic or noncarcinogenic toxicity effects of uranium (Title 40, Part 192, of the *Code of Federal Regulations* [40 CFR Part 192]). Because the NCP states that proposed regulations are only TBCs, the proposed MCL standard is not an ARAR. Further, the NCP sets out a process to determine whether a standard is relevant and appropriate to a particular remediation activity at the site. The 30 pCi/L is relevant in that it applies to the same contamination (uranium) in the same medium (groundwater). However, this standard was developed for

environmental conditions not pertinent to the WSCP and WSOW. As such, it is questionable whether this standard is appropriate as applied to contaminated groundwater at the WCSP and the WSOW.

Under the NCP, if ARARs are not available, alternative criteria such as risk-based values may be developed. Because there are no ARARs for eight of the nitroaromatic compounds that are COCs, it is appropriate to develop risk-based values for these compounds (risk-based values are developed on the basis of RfDs or slope factors provided by the EPA). Risk-based values were also developed for uranium.

In accordance with the EPA approach set out in the preamble to the NCP (EPA 1990a), exposure assessments for current and future land use involve developing reasonable maximum estimates of exposure for both current and potential future land use conditions. The exposure analysis for current land use conditions is used to determine whether a human health or environmental threat might be posed by existing conditions. The analysis of future land use conditions is used to provide decision makers with an understanding of exposures that may potentially occur, including a qualitative analysis of the likelihood that the assumed future land use will occur. The reasonable maximum exposure estimate for future use provides the basis for developing protective exposure levels. Concentrations of carcinogenic contaminants equivalent to the 1×10^{-4} and 1×10^{-6} risk range were estimated for both the recreational and residential scenarios to provide a range of information for risk management purposes. Calculations were also performed to determine the concentrations of noncarcinogenic contaminants that would be equivalent to a hazard index of 1 for both scenarios. Assumptions and methodologies were similar to those used for risk estimates in the BRA (DOE and DA 1998a) and are further discussed in Appendix B of this FS.

For the purpose of the evaluations and comparisons performed in this FS, PRGs for the contaminants of concern were identified using available ARARs, as follows: 5 µg/L for TCE, 10 mg/L for nitrate as nitrogen (nitrate-N), 0.11 µg/L for 2,4-DNT, 1.0 µg/L for 1,3-DNB, and 17 µg/L for nitrobenzene.

For the remaining COCs, PRGs were determined from risk-based values for the recreational visitor scenario. Likely future land uses for the WSCP and the WSOW are expected to be similar to current land uses. Current land uses for both areas are considered recreational. Table 1.2 presents a

TABLE 1.2 Summary of Regulatory Criteria, Risk-Based Values, and Preliminary Remediation Goals for Groundwater Contaminants of Concern

			Risk-Based Values[b]				
			Residential Scenario		Recreational Scenario		
Contaminant of Concern	Unit	Regulatory Criteria[a]	10^{-6} to 10^{-4} Carcinogenic Risk Range	Hazard Index of 1	10^{-6} to 10^{-4} Carcinogenic Risk Range	Hazard Index of 1	Proposed PRGs for the GWOUs[c]
TCE	µg/L	5	7.7 – 770	NA[d]	680 – 68,000	NA	5
Nitrate-N	mg/L	10	NA	58[e]	NA	5,100	10
2,4,6-TNT	µg/L	2[f]	2.8 – 280	18	250 – 25,000	1,600	250
2,4-DNT	µg/L	0.11[g]	0.13 – 13	73	11 – 1,100	6,400	0.11
2,6-DNT	µg/L	-[h]	0.13 – 13	37	11 – 1,100	3,200	11
2-Amino-4,6-DNT	µg/L	-	NA	2.2	NA	190	190
4-Amino-2,6-DNT	µg/L	-	NA	2.2	NA	190	190
1,3,5-TNB	µg/L	-	NA	1.8	NA	160	160
1,3-DNB	µg/L	1.0[g]	NA	3.7	NA	320	1.0
m-Nitrotoluene	µg/L	-	NA	37	NA	3,200	3,200
o-Nitrotoluene	µg/L	-	NA	37	NA	3,200	3,200
p-Nitrotoluene	µg/L	-	NA	37	NA	3,200	3,200
Nitrobenzene	µg/L	17[g]	NA	18	NA	1,600	17
Uranium	pCi/L	30	0.90–90[i]	110 µg/L[j]	78 – 7,800[i]	9,600 µg/L[j]	78

[a] The values in this column include MCLs, EPA drinking water health advisories, Missouri water quality standards, Missouri health advisories for groundwater, and groundwater standards for remedial actions at inactive uranium processing sites. A detailed tabulation of ARARs is presented in Appendix A.

[b] Risk-based values were estimated using a residential scenario considered as the upper-bound case. Estimates for the recreational scenario were calculated for groundwater using similar assumptions for estimating exposure to springwater. Details regarding risk methodology and equations used for calculations are presented in the BRA (DOE and DA 1998a) and in Appendix B of this FS. The likely future receptor is similar to the current receptor, a recreational visitor. The recreational visitor under current land use does not have access to the actual groundwater.

[c] The proposed PRGs for TCE, nitrate-N, 2,4-DNT, 1,3-DNB, and nitrobenzene are based on ARARs. PRGs for carcinogenic nitroaromatic compounds (i.e., 2,4,6-TNT, 2,6-DNT, and uranium) are based on concentrations that are equivalent to the 1×10^{-6} risk for the recreational scenario. PRGs for noncarcinogenic nitroaromatic compounds (i.e., 2-amino-4,6-DNT, 4-amino-2,6-DNT, 1,3,5-TNB, m-nitrotoluene, o-nitrotoluene, and p-nitrotoluene) are based on concentrations equivalent to a hazard index of 1 for each compound. See Section 1.5 for discussion.

[d] NA = not applicable; a slope factor or reference dose, whichever is appropriate, is not available.

[e] Value based on an adult residential receptor; the value for infants would be less because nitrate-N would be more toxic to infants than adults.

[f] EPA drinking water health advisory; considered to be a TBC.

[g] Missouri water quality standard that is an ARAR.

[h] A hyphen (-) indicates that no regulatory criteria are available.

[i] Based on radiological risk for uranium.

[j] Based on chemical toxicity of uranium.

tabulation of the regulatory criteria, risk-based values, and proposed PRGs. The PRGs for 1,3-DNB and nitrobenzene are not exceeded on the basis of data reported since 1995.

For 2,4,6-TNT and 2,6-DNT — considered to be carcinogenic compounds — PRGs were identified as those concentrations that are equivalent to the 1×10^{-6} risk for the recreational scenario, as follows: 250 and 11 µg/L, respectively. These concentrations are similar to (in fact, slightly lower than) the concentrations that are equivalent to the 1×10^{-4} risk for a residential scenario. The maximum concentration reported for 2,4,6-TNT from the 1995 joint sampling rounds was 30 µg/L. This indicates that 2,4,6-TNT concentrations in the current groundwater system may already be protective of both the recreational and residential scenarios. The maximum concentration of 2,6-DNT reported in the 1995 joint sampling rounds was 15 µg/L. Although this concentration is slightly greater than the proposed PRG of 11 µg/L, it is still within the acceptable risk range for the recreational scenario.

The remaining nitroaromatic compounds are considered noncarcinogenic compounds. The maximum concentrations reported for these compounds from the 1995 joint sampling results are well within the concentrations equivalent to a hazard index of 1 for the recreational scenario for each compound (see Table 1.2). The maximum concentrations were reported as 35 µg/L for 2-amino-4,6-DNT, 26 µg/L for 4-amino-2,6-DNT, 39 µg/L for 1,3,5-TNB, 100 µg/L for m-nitrotoluene, 7.7 for o-nitrotoluene, and 30 µg/L for p-nitrotoluene. Uranium concentrations have been reported to be less than 78 pCi/L on the basis of recent data reported since 1996. Table 1.3 lists the wells at which PRGs are exceeded for contaminants of concern considered for WSCP and WSOW groundwater. Figures 1.13, 1.14, and 1.15, illustrate locations where TCE, nitrates, and 2,4-DNT PRGs are exceeded at the WSCP. Figure 1.16 illustrates locations where 2,4-DNT PRGs are exceeded at the WSOW. Overall, the number of locations where the PRG for 2,4-DNT is exceeded encompasses areas where exceedances of PRGs for the other nitroaromatic compounds occur.

1.6 ORGANIZATION OF THE REPORT

The remainder of this FS is organized as follows:

- Chapter 2 presents the identification and evaluation of potential response technologies;

TABLE 1.3 Wells with Contaminant Concentrations Exceeding PRGs[a]

Well	TCE (µg/L)	Nitrate (mg/L)	1,3,5-TNB (µg/L)	2,4,6-TNT (µg/L)	2,4-DNT (µg/L)	2,6-DNT (µg/L)	2-Amino-4,6-DNT (µg/L)	4-Amino 2,6-DNT (µg/L)	2-Nitro-toluene (µg/L)	3-Nitro-toluene (µg/L)	4-Nitro-toluene (µg/L)	Nitro-benzene (µg/L)	1,3-DNB (µg/L)	Uranium (pCi/L)
PRG[b]	**5**	**10**	**160**	**250**	**0.11**	**11**	**190**	**190**	**3,200**	**3,200**	**3,200**	**17**	**1.0**	**80**
WSCP: Weathered														
MW-2001	-[c]	49	-	-	0.13	-	-	-	-	-	-	-	-	-
MW-2002	-	130	-	-	-	-	-	-	-	-	-	-	-	-
MW-2003	-	310	-	-	0.15	-	-	-	-	-	-	-	-	-
MW-2005	-	66	-	-	-	-	-	-	-	-	-	-	-	-
MW-2006	-	-	-	-	0.14	-	-	-	-	-	-	-	-	-
MW-2010	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MW-2011	-	-	-	-	0.20	-	-	-	-	-	-	-	-	-
MW-2012	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MW-2013	-	-	-	-	0.36	-	-	-	-	-	-	-	-	-
MW-2014	-	-	-	-	0.16	-	-	-	-	-	-	-	-	-
MW-2030	-	-	-	-	0.25	11	-	-	-	-	-	-	-	-
MW-2032	-	56	-	-	-	-	-	-	-	-	-	-	-	-
MW-2033	-	-	-	-	0.55	-	-	-	-	-	-	-	-	-
MW-2037	1,300	290	-	-	0.56	-	-	-	-	-	-	-	-	-
MW-2038	9,000	900	-	-	1.7	-	-	-	-	-	-	-	-	-
MW-2039	-	52	-	-	-	-	-	-	-	-	-	-	-	-
MW-2040	-	230	-	-	-	-	-	-	-	-	-	-	-	-
MW-2041	-	300	-	-	-	-	-	-	-	-	-	-	-	-
MW-3003	-	440	-	-	-	-	-	-	-	-	-	-	-	-
MW-3023	-	210	-	-	5.0	-	-	-	-	-	-	-	-	-
MW-3025	40	520	-	-	-	-	-	-	-	-	-	-	-	-
MW-3027	-	62	-	-	-	-	-	-	-	-	-	-	-	-
MW-4001	-	40	-	-	1.3	-	-	-	-	-	-	-	-	-
MW-4002	-	-	-	-	0.14	-	-	-	-	-	-	-	-	-
MW4006	-	14	-	-	0.16	-	-	-	-	-	-	-	-	-
MW-4013	-	94	-	-	-	-	-	-	-	-	-	-	-	-
MW-4015	-	-	-	-	0.19	-	-	-	-	-	-	-	-	-
WSCP: Unweathered														
MW-3024	60	370	-	-	0.13	-	-	-	-	-	-	-	-	-
MW-3026	-	220	-	-	-	-	-	-	-	-	-	-	-	-
MW-4011	-	170	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 1.3 (Cont.)

Well	TCE (µg/L)	Nitrate (mg/L)	1,3,5-TNB (µg/L)	2,4,6-TNT (µg/L)	2,4-DNT (µg/L)	2,6-DNT (µg/L)	2-Amino-4,6-DNT (µg/L)	4-Amino 2,6-DNT (µg/L)	2-Nitro-toluene (µg/L)	3-Nitro-toluene (µg/L)	4-Nitro-toluene (µg/L)	Nitro-benzene (µg/L)	1,3-DNB (µg/L)	Uranium (pCi/L)
PRG[b]	**5**	**10**	**160**	**250**	**0.11**	**11**	**190**	**190**	**3,200**	**3,200**	**3,200**	**17**	**1.0**	**80**
WSOW: Weathered														
MWS-12	-	-	-	-	8.8	15	-	-	-	-	-	-	-	-
MWS-17	-	-	-	-	1.1	13	-	-	-	-	-	-	-	-
MWS-21	800	520	-	-	0.94	-	-	-	-	-	-	-	-	-
WSOW: Overburden														
MWV-9	-	-	-	-	20	-	-	-	-	-	-	-	-	-
MWV-24	-	-	-	-	0.13	-	-	-	-	-	-	-	-	-
USGS-4	-	-	-	-	1.5	-	-	-	-	-	-	-	-	-

[a] Concentrations are maximum concentrations detected during the 1995 joint DOE and DA sampling.

[b] PRGs are risk-based values for the recreational scenario, except for TCE, uranium, 2,4-DNT, 1,3-DNB, and nitrobenzene.

[c] A hyphen (-) indicates that the maximum contaminant concentration detected is below the proposed PRG.

[d] Concentration is suspected to be biased high because of the bentonite grout used for installing the well; a more recent (September 1996) concentration reported for MW-4024 was 4.1 pCi/L.

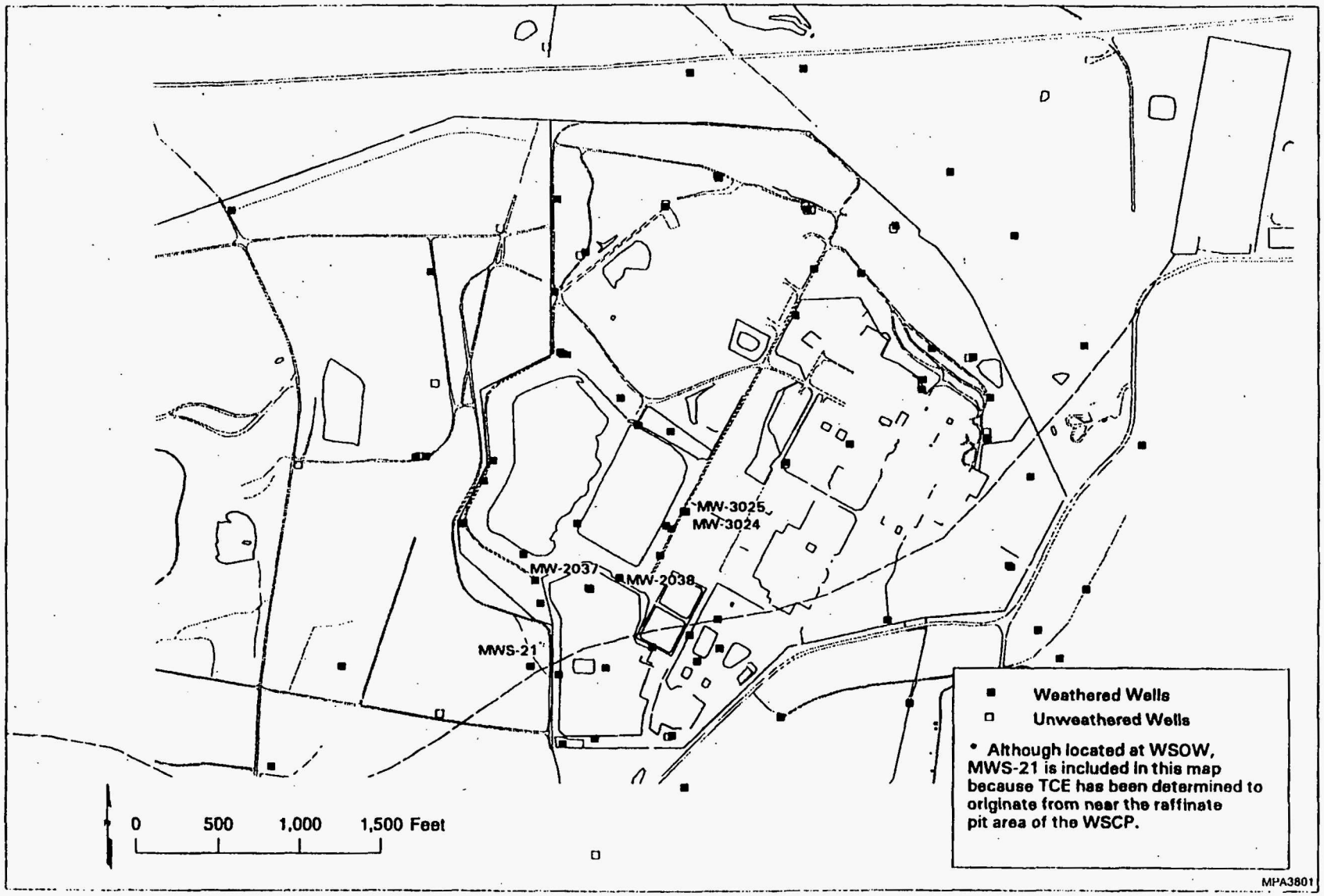

FIGURE 1.13 Locations of Wells at the WSCP Containing TCE Exceeding Proposed PRGs

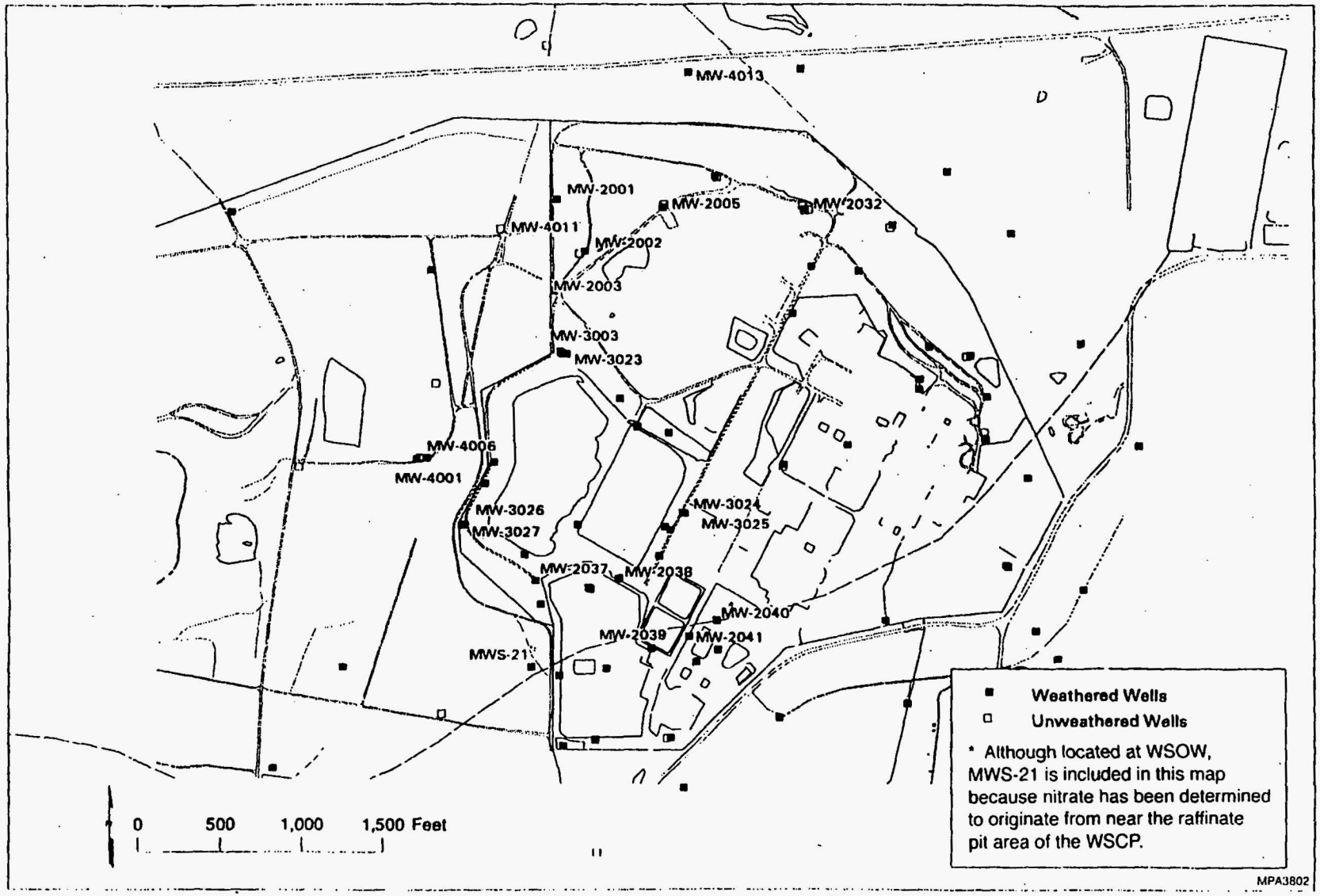

FIGURE 1.14 Locations of Wells at the WSCP Containing Nitrate Exceeding Proposed PRGs

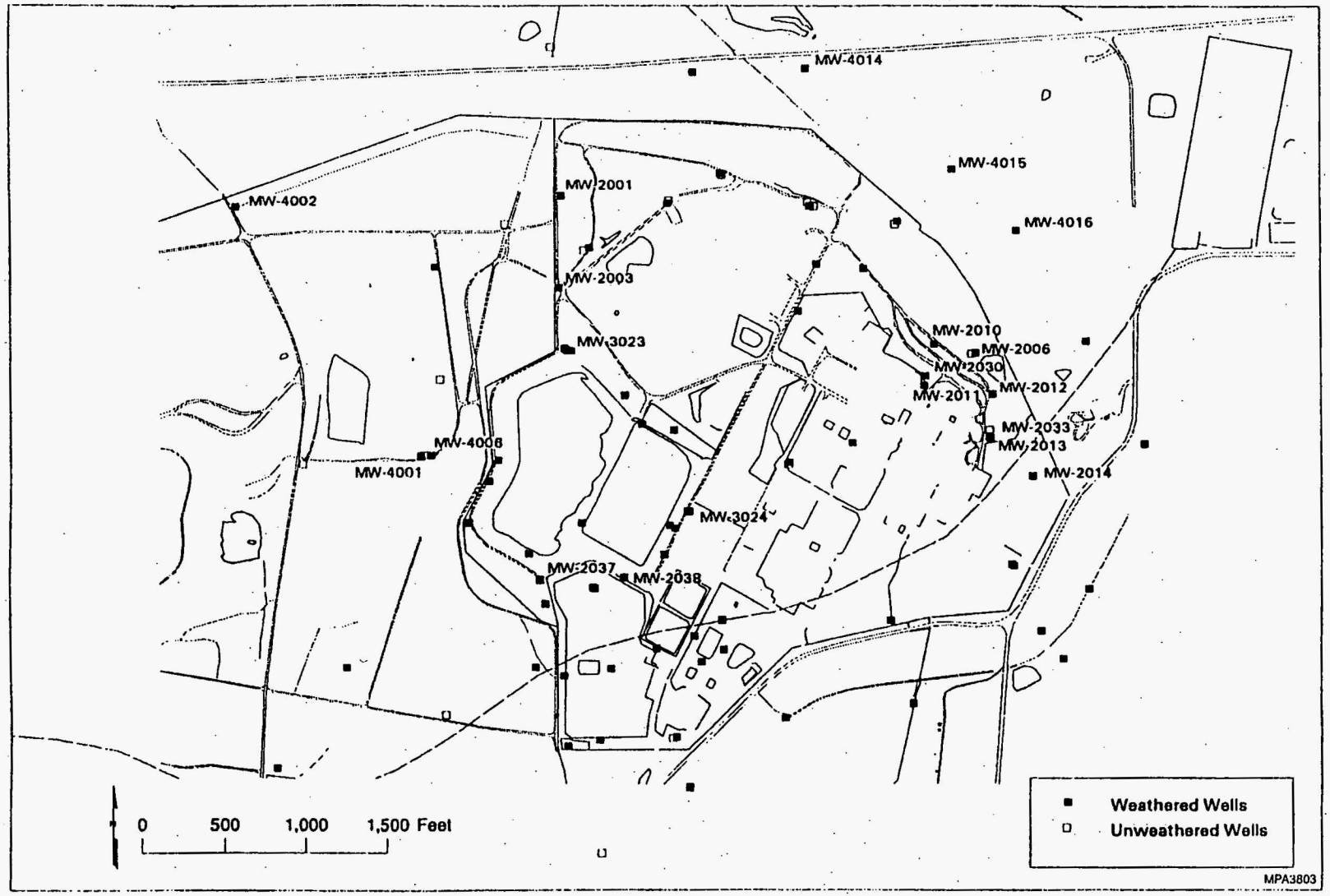

FIGURE 1.15 Locations of Wells at the WSCP Containing 2,4-DNT Exceeding Proposed PRGs

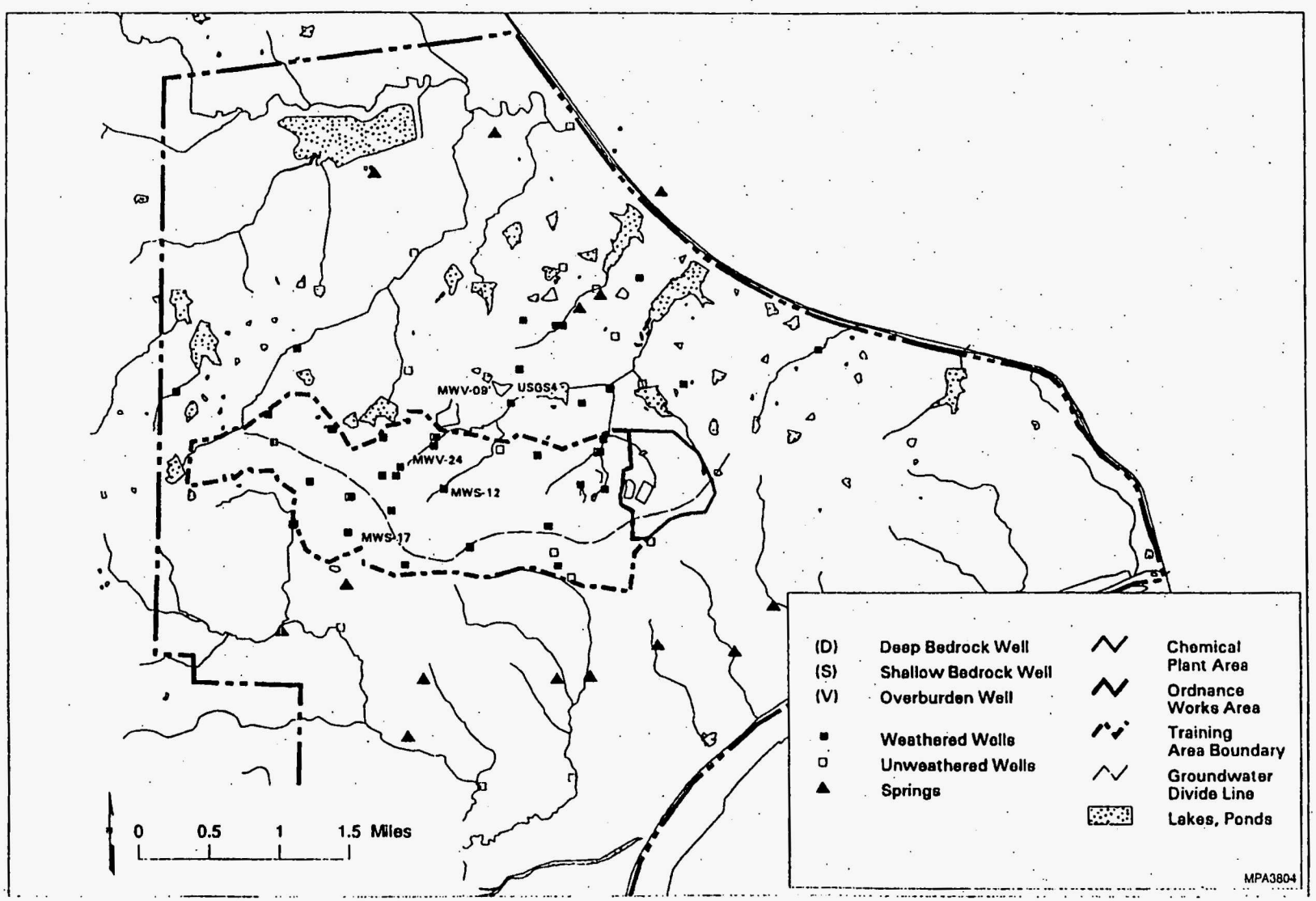

FIGURE 1.16 Locations of Wells at the WSOW Containing 2,4-DNT Exceeding Proposed PRGs

- Chapter 3 presents the development and screening of preliminary alternatives;
- Chapter 4 gives a detailed description and evaluation of the final alternatives;
- Chapter 5 is a comparative analysis of the final alternatives; and
- Chapter 6 lists the references cited in the report.
- Appendix A discusses and lists the regulatory requirements potentially applicable or relevant and appropriate to the remedial action.
- Appendix B presents details of the calculations for PRGs.
- Appendices C through G provide discussions of the methodologies used to analyze certain alternatives considered in the EIS:
  - Appendix C, Methodology and Assumptions Used to Calculate the Potential Number of Extraction Wells for the WSCP and the WSOW;
  - Apppendix D, Determination of Constructed Wetland Design for Alternative 6: Groundwater Removal, On-Site Treatment Using Phytoremediation;
  - Appendix E, Modeling of Trichloroethylene Contaminant Transport and Degradation Using the Transport Code "BIOSCREEN";
  - Appendix F, Methodology and Assumptions Used to Determine the Costs of the Various Alternatives in this Feasibility Study;
  - Appendix G, Analytical Methodologies Used to Address Potential Environmental Impacts for Alternative 2: Monitoring with No Active Remediation.

2 IDENTIFICATION AND SCREENING OF TECHNOLOGIES

2.1 SCREENING CRITERIA

The criteria for identifying potentially applicable technologies are provided in EPA guidance (EPA 1988a) and in the NCP (EPA 1994). The primary requirements for a final remedy are that it be both protective of human health and the environment and cost effective. Hence, technology screening focuses on these two factors. Additional selection criteria include the following:

- Preferred remedies are those in which the principal element is treatment to permanently or significantly reduce the toxicity, mobility, or volume of hazardous substances, pollutants, or contaminants;
- Where practical treatment technologies are available, off-site transport and disposal without treatment is the least preferred alternative; and
- Permanent solutions and alternative treatment technologies or recycle/resource recovery technologies should be assessed and used to the maximum extent practicable.

These criteria have been considered in identifying and screening technologies to determine the appropriate components of remedial action alternatives for the contaminated groundwater at the WSCP and WSOW. Protection of human health and the environment was the primary consideration for determining how the contaminated groundwater should be managed.

On the basis of current knowledge of the nature and extent of groundwater contamination at the WSCP and the WSOW, the following are the general response actions that could be implemented to help reduce exposure to the contaminants or to reduce or remove elevated concentrations of TCE (WSCP only), nitroaromatic compounds, nitrates, and uranium: (1) institutional controls and monitoring; (2) natural processes; (3) in-situ containment; (4) in-situ treatment; or (5) removal, storage, ex-situ treatment, and disposal. Technology types and process options that could be used to implement each general response action (3 through 5) are presented schematically in Figure 2.1. Specific application of these technology types and process options to

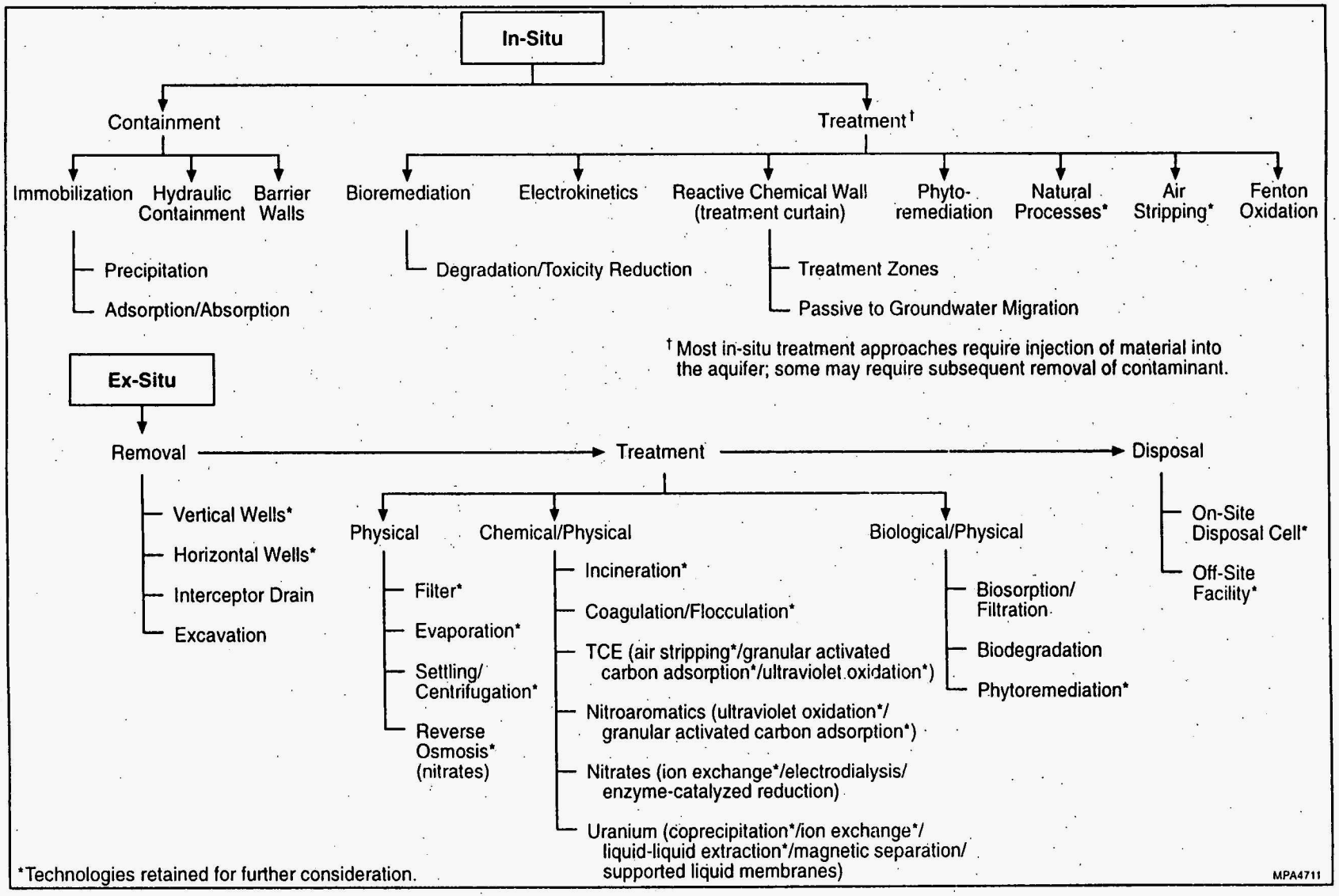

FIGURE 2.1 Potential Technologies for Groundwater Remediation at the WSCP and the WSOW

conditions at the WSCP and WSOW was evaluated to determine which would be the most appropriate for groundwater remediation.

These technologies were screened on the basis of effectiveness, implementability, and cost, and are defined as follows:

- Effectiveness — in terms of protecting human health and the environment in both the short term and the long term; minimizing toxicity, mobility, or volume; complying with ARARs; and achieving protection in a reasonable time frame.
- Implementability — in terms of technical feasibility, resource availability, and administrative feasibility.
- Cost — in terms of comparing costs (i.e., low, moderate, or high) in both the short term (capital) and long term (operation and maintenance [O&M]) for technologies of similar performance and/or implementability.

2.2 TECHNOLOGY IDENTIFICATION AND SCREENING

2.2.1 Institutional Controls and Monitoring

Institutional controls are measures that preclude or minimize public exposure by limiting access to or use of contaminated groundwater. Institutional controls include measures to restrict access, such as security guards, ownership, and use or deed restrictions. These measures do not reduce contaminant toxicity, mobility, or volume, but they can reduce the potential for human exposure to the contaminated groundwater. Institutional control measures that apply solely to groundwater, such as groundwater restrictions, may be used to prohibit or limit the drilling of wells for the purpose of groundwater consumption. Monitoring is a measure that provides supporting information regarding contaminant concentrations and the need for maintaining or implementing institutional controls while remedial actions are being carried out.

The screening analysis for institutional controls and monitoring is summarized in Table 2.1. On the basis of effectiveness, implementability, and cost, all of these measures were retained for further consideration.

TABLE 2.1 Summary of Screening Analysis for Institutional Controls

Institutional Control Measure	Effectiveness	Implementability	Cost
Groundwater access restrictions	The area where groundwater contamination is highest could be restricted by imposing barriers, such as well caps, which could control exposure to contaminated groundwater.	Access restriction measures would be easy to implement, and resources would be readily available.	Low
Ownership and use or deed restrictions	The DOE and DA have accountability for as long as contamination is present. This measure would permit the control of public exposure to on-site contamination by restricting access and use. The state owns the surrounding wildlife areas, and recreational use would not include groundwater use.	Ownership and use or deed restrictions would be easy to implement, and resources would be readily available.	Low
Monitoring	An extensive groundwater monitoring program is in place at the WSCP and WSOW. This measure could support the mitigation of potential exposures by providing data on the extent of contamination and the effectiveness of primary control measures such as containment or removal.	Monitoring would be easy to implement; the existing monitoring network could be used to provide long-term protection.	Low

2.2.2 Natural Processes

Naturally occurring processes can contribute to cleaning up groundwater and soil contaminated with various toxic and hazardous materials. With time, these processes gradually reduce the hazards of contamination. Two types of natural processes can be considered: (1) physical/chemical processes whereby the contaminant concentration would be reduced through chemical or physical means and (2) biological processes whereby the contaminant is broken down or absorbed by microbes or plants.

The first classification includes a number of processes such as dilution, absorption, adsorption, and chemical reactions. Biological processes, the second classification, includes two broad categories: accumulation and degradation by microbes and accumulation and degradation by plants.

Extensive, ongoing remedial actions at both the WSCP and the WSOW will have removed contaminated structures and soil to achieve site-derived cleanup levels. The remaining contamination

in the soil and groundwater is expected to decrease over time because the primary water source is infiltration from rainwater and runoff, which will provide a clean source of water to dilute the contaminant concentrations in the aquifer.

The sorption process could also play a role in determining the fate of the contaminants in groundwater. Sorption of a contaminant refers to the tendency of the molecules to be bound to the surface (adsorption) of and to internal sites (absorption) in the bulk solid phase of the aquifer. This process occurs primarily in the soil layers above the bedrock since the soil has more sorption sites.

Two parameters are important in describing this interaction between the contaminant and the solid phase (soil). The total sorption capacity is proportional to the total number of available sorption sites. When all of the sorption sites are occupied, the sorption capacity is exhausted, and contaminant concentrations are no longer attenuated as the groundwater passes through the solid phase. A second parameter of importance is the strength of the binding between the contaminant and the sites in or on the solid phase. This strength is related to the value of a distribution coefficient, K_d. K_d values are specific to a given contaminant in relation to a particular type of soil. Understanding the movement of a given contaminant through an aquifer depends in part on knowing the K_d values for each soil type and the groundwater flow conditions.

The K_d values for TCE, nitroaromatic compounds, and nitrates in soil at the WSCP and WSOW are expected to be low (DOE and DA 1998b), which means that minimal sorption is expected to be taking place. On the other hand, the K_d value for uranium is higher, which suggests that uranium is more likely to be sorbed than the other contaminants. Less sorption would be expected for all contaminants in the bedrock portion of the aquifer because of fewer accessible sorption sites. Adsorption of nitroaromatic compounds is prevented in the presence of highly hydrated cations such as Ca^{2+} (Haderlein et al. 1996); therefore, little, if any, adsorption of nitroaromatic compounds is expected to be occurring in the limestone bedrock. In any areas of high organic content in the aquifer (e.g., from decaying plants), there is a much higher probability of sorption (and reaction) of the organic contaminants and of uranium.

Chemical reactions are those reactions in which ions or compounds react with other species to form new ions or compounds. These reactions generally involve electron exchange or oxidation-reduction (redox), which results in the oxidation of one species (electron loss) and the reduction of

the other (electron gain). One such example is the precipitation of uranium from solution as uranium dioxide (UO_2) following the reduction of the soluble UO_2^{2+} ion. Thus, one controlling factor is the relative affinity of species for electrons. Another major controlling factor in chemical reactions involves the concentrations of the different species in solution and their equilibria with any solid phases. In a groundwater aquifer such as at that at the WSCP and WSOW, most of the chemical reactions taking place involve dissolved inorganic species. The majority of organic contaminants in the aquifer are more likely to be involved in biological degradation reactions.

Biological processes are important for the natural degradation of organic compounds in the environment. The degradation of TCE by various microbe populations has been extensively studied (Lu et al. 1989; Hopkins et al. 1993; Krumme et al. 1993; Enzien et al. 1994; Leahy et al. 1996). Intrinsic bioremediation of TCE has been shown to occur. At some sites, biological activity is being supported under anaerobic conditions by other organic contaminants such as acetone, methanol, or BTEX compounds (benzene, toluene, ethylbenzene, and xylenes), and the degradation of TCE is the result of cometabolism (Lee et al. 1995; Major et al. 1995; Wiedemeier et al. 1997). Cometabolism may also have played a role in degradation of TCE at other sites (Guest et al. 1995). The intrinsic anaerobic biodegradation of TCE has been observed in the absence of anthropogenic cometabolites such as acetone and methanol (Martin and Imbrigiotta 1994; Cox et al. 1995; Ellis et al. 1997; Weaver et al. 1997). Under such conditions, the microorganisms responsible for the degradation may be using naturally occurring organic carbon concentrations as a substrate (Wiedemeier et al. 1997). However, the vinyl chloride degradation product may also be degraded by iron (III) reduction or aerobic respiration (Weidemeier et al. 1997).

A number of investigators have examined the efficacy of microbial degradation as a mechanism for breaking up the nitroaromatic contaminants. Most of these studies have used preselected microbial communities rather than the natural indigenous community of microbes. The particular microbial communities studied have included sewage (Hallas and Alexander 1983), bioslurry (Funk et al. 1993), composting (Kaplan and Kaplan 1982), particular strains of bacteria (Spanggora et al. 1991; Boopathy et al. 1993, 1997), and particular fungi (Fernando et al. 1990; Valli et al. 1992). Only one study, which was carried out at a munitions-contaminated site (Bradley et al. 1994), used the natural indigenous microbial community present at the contaminated site. Degradation of nitroaromatic compounds has been shown to occur under both aerobic and anaerobic

conditions (Spain 1996). A number of studies have shown that microbial denitrification occurs in nitrate-contaminated groundwater (Smith and Duff 1988; Bottcher et al. 1990; Smith et al. 1996); however, because the process is electron-donor-limited (Smith et al. 1991), a carbon substrate such as ethanol must be added to stimulate activity. Accumulation or precipitation of uranium by microbes is also possible (Lovely et al. 1993; Barton et al. 1996; Uhrie et al. 1996).

Although TCE can be degraded by certain microbial populations, many factors appear to be important in determining the rate of degradation. The addition of a carbon substrate (e.g., toluene, benzene, or phenol) to supply energy to the microbes greatly enhances the degradation process; the microbes apparently are unable to derive much energy directly from the TCE. Therefore, any natural biological degradation of TCE at the WSCP might be expected to occur at a slow rate. Biological degradation of the nitroaromatic compounds could be occurring at the WSCP and WSOW. Some studies have shown that toxic shock occurs at higher concentrations (EPA 1993), thereby relegating any biological activity to the fringe areas where concentrations are lower. However, concentrations of nitroaromatic compounds in groundwater at the WSCP and WSOW (DOE and DA 1998b) are not expected to be high enough to cause toxic shock for most microorganisms capable of degrading nitroaromatic compounds (Kaplan 1992). Nitrates might also be expected to be degraded in the aquifer because anaerobic conditions favor nitrate decomposition.

Plant activity (vegetation) can also accumulate or degrade TCE, nitroaromatic compounds, nitrates, and uranium in the environment (see Section 2.2.4.6). However, most of this activity occurs within a zone from the surface down to about 3 m (10 ft). Therefore, the natural vegetative activity at the WSCP and WSOW is not expected to be a major factor in attenuating the contaminant concentrations at greater depths.

The screening analysis for natural processes is summarized in Table 2.2. On the basis of this evaluation, natural processes have been retained as potentially applicable to attenuating contaminant concentrations in groundwater.

TABLE 2.2 Summary of Screening Analysis for In-Situ Containment and Treatment Measures

In-Situ Measure	Effectiveness	Implementability	Cost
Natural attenuation	Groundwater concentrations of contaminants are expected to slowly diminish over time due to dilution because the contaminant source has been removed. The primary water source is infiltration from rainwater and runoff, which provides a clean source of water to dilute the contaminant concentrations in the aquifer. Microbial degradation of TCE, nitroaromatic compounds, and nitrates might be occurring. Sorption of nitroaromatic compounds and uranium could be limiting groundwater concentrations of these contaminants.	Natural attenuation would be easy to implement, but it might be difficult to show its effectiveness in the near term.	Low
Physical barrier	A physical barrier — such as a slurry wall or plastic sheeting — could effectively reduce lateral migration. The barrier would act to confine contamination to the currently affected areas but would not act to lower the contaminant concentrations. However, local areas of high hydraulic pressure exerted by natural conduits underground would likely cause the barrier to fail.	Could not be implemented by conventional methods and equipment because of the depth of contamination in bedrock.	High
Immobilization	Immobilization of the TCE, nitroaromatic compounds, nitrates, and uranium through either precipitation or adsorption/absorption would effectively remove the contaminants from the groundwater.	Could not be implemented because of the low permeability of the aquifer.	Low to moderate
Bioremediation	Microorganisms could be used in-situ to break down TCE, nitroaromatic compounds, and nitrates into less toxic materials. Such an approach cannot be used with uranium.	Could not be implemented because the low permeability of the aquifer would preclude injection of the microorganisms and their feed.	Moderate
Electrokinetics	Underground electrodes cause preferential migration of chemical species in the aquifer to treatment zones at or around electrodes. Shown to be effective for TCE in an unsaturated soil field test. Effectiveness of TCE in saturated bedrock is uncertain. Effectiveness of full-scale remediation for nitroaromatic compounds, nitrates, and uranium is not well established.	Could be implemented by conventional methods and equipment.	Moderate to high

TABLE 2.2 (Cont.)

In-Situ Measure	Effectiveness	Implementability	Cost
Reactive wall	A permeable barrier is placed across the contaminated groundwater flow path. The barrier contains species that either react with the contaminant to remove it from solution or catalyze the breakdown of the contaminant. A number of materials have been identified that are capable of removing TCE, nitroaromatic compounds, nitrates, and uranium from groundwater.	Could not be implemented by conventional methods and equipment because of contamination in the bedrock and the existence of natural underground conduits.	High
Air stripping	Air is passed through the water in a well to extract dissolved TCE, thereby generating a recirculation pattern in the aquifer surrounding the well.	May be implementable in certain areas of the WSCP.	Moderate
Fenton oxidation	Hydrogen peroxide (H_2O_2) and ferrous sulfate ($FeSO_4$) are injected into an aquifer to produce hydroxyl radicals, which degrade (oxidize) most organic contaminants, including TCE.	Low and variable permeability make implementation uncertain.	Low to moderate
Phytoremediation	Vegetation is used to preferentially absorb contaminants from soil and groundwater and either break down the contaminants or retain them in the biomass of the vegetation. Initial studies have shown that the measure is effective with the contaminants of interest, but only in near-surface layers.	Could not be implemented to a depth of approximately 15 m (50 ft) in the short term.	Low

2.2.3 In-Situ Containment

In-situ (in-place) containment consists of technologies that confine contaminated groundwater at its current location. In-situ containment technologies include the erection of barrier walls, hydraulic containment, or the immobilization of the contaminant species at its current location. These technologies reduce contaminant mobility and the associated potential for exposure, but, except for one variation of hydraulic containment, they do not reduce contaminant toxicity or volume.

Current groundwater discharges to surface water outside the WSCP and WSOW do not have contaminant concentrations high enough to warrant remedial action, even though the groundwater travel times from the contaminated areas to outside surface waters may, in some

instances, be on the order of a few hours. Therefore, the use of in-situ containment may not provide any benefit.

2.2.3.1 Barrier Walls

The use of a physical barrier to stop groundwater migration of contaminants is not feasible at the WSCP and WSOW because the contamination is too widespread and too deep in some areas, and it would not be effective in controlling groundwater flow. Contamination in this region is spread out over several square miles (DOE and DA 1998b); a groundwater divide runs the length of the region. Therefore, two barrier walls would have to be erected, one on each side of the divide and each approximately 5 km (3 mi) long. The high cost of installing such long walls would not be reasonable because of the relatively low concentrations of contaminants in most affected areas within the region. Even if barriers were to be considered in localized areas, contamination has been found at depths greater than 15 m (50 ft) in bedrock in some areas. Implementing a barrier wall technology would therefore be difficult because conventional trenching equipment cannot be used at such depths or in bedrock formations. In addition, channeling of the groundwater flow in natural conduits in the shallow aquifer within the Burlington-Keokuk Limestone could not be effectively controlled (because of high hydraulic pressures in localized areas).

The screening analysis for in-situ containment is summarized in Table 2.2. The technology of a physical barrier as potentially applicable to a groundwater remedial action was rejected on the basis of effectiveness, implementability, and cost.

2.2.3.2 Hydraulic Containment

Hydraulic containment of a contaminant in an aquifer can be achieved through the use of pumping wells, injection wells, or a combination of the two (EPA 1996b). Hydraulic containment is also the primary objective of pump-and-treat systems. Further discussion of groundwater removal for application in pump-and-treat systems can be found in Section 2.2.5.

The hydraulic control exerted by a vertical pumping well relies on the creation of a capture zone where water is drawn towards the well. A line of wells with overlapping capture zones can be situated downgradient of the contamination to form a barrier to further migration. A different type of barrier to migration, a pressure ridge, can also be formed by injecting uncontaminated water

through a series of injection wells. The resulting increase in hydraulic pressure prevents groundwater from flowing along its original path. Pressure ridges are often used in conjunction with pump-and-treat systems, in which the treated water extracted from within the contaminated area is used for injection (EPA 1996b).

Implementation of hydraulic containment, other than pump-and-treat in specific localized areas as discussed in Section 2.2.5, is not feasible. Creating a proper capture zone in this area may be problematic because of the low permeability (Cohen et al. 1994) found over most of the WSCP and WSOW. Hydraulic conductivities in the WSCP range from 10^{-6} to 10^{-2} cm/s; the range in the WSOW is even lower at 10^{-8} to 10^{-5} cm/s (DOE and DA 1998b). In the regions in the WSCP where the aquifer permeability is highest, such as the TCE-contaminated area south of the raffinate pits, hydraulic control by the use of a capture zone downgradient would not be very effective compared to a pump-and-treat approach because of low groundwater flow rates. Because low-levels of contamination are widespread, any attempt at confining areas with higher contaminant concentrations in areas of higher permeability with pressure ridges would also result in the acceleration of contaminants away from the area on the other side of the pressure ridges.

The karst formations in the aquifer would also compromise the effectiveness of capture zones and pressure ridges in the areas of the WSCP and WSOW. Identifying and containing all preferential flows in even a localized area would be impractical. For pressure ridges, it would be difficult to maintain the proper water pressures in these formations; or, inordinately large amounts of water would be used in the attempt to maintain a uniform pressure ridge.

The screening analysis for in-situ containment is summarized in Table 2.2. The technology of hydraulic containment as potentially applicable to groundwater remedial action was rejected on the basis of effectiveness and implementability because of low permeability in most areas, widespread low-levels of contamination, and the existence of preferential flow conduits.

2.2.3.3 Immobilization

Immobilization of the contaminant species in-situ relies on either precipitation of the dissolved contaminant out of solution through an induced chemical reaction, or binding (adsorption or absorption) of the contaminant by an immobile solid phase material within the groundwater aquifer. Immobilization of TCE and nitroaromatic compounds through precipitation could not be

implemented because chemical reaction changes the nature of the contaminant and generally leads to degradation in groundwater systems (see Sections 2.2.4 and 2.2.6 for discussion of degradation in in-situ and ex-situ treatment). Precipitation is also not feasible for nitrates because of the need to inject metals. Precipitation, including the use of microorganisms, could be used to immobilize uranium (Lovely et al. 1993; Barton et al. 1996; Uhrie et al. 1996), but uranium concentrations in groundwater are only slightly above background levels.

Either immobilization process, precipitation or binding, would require the injection of material into the aquifer. However, the low permeability of the aquifer at the WSOW (hydraulic conductivity ranges from 10^{-8} to 10^{-5} cm/s) and the WSCP makes the injection of materials to bind the nitroaromatic compounds impractical, especially in the case of clay-based sorption materials. Injection into the aquifer in the areas of higher permeability in the WSCP (hydraulic conductivity $\leq 10^{-2}$ cm/s) may still be problematic because of potential clogging of the injection wells and nonuniform delivery, which results from the bulky nature of the materials required to immobilize the organic contaminants by sorption — organic materials for TCE or nitroaromatic compounds or clays for nitroaromatic compounds.

The screening analysis for in-situ containment is summarized in Table 2.2. On the basis of implementability, the inability to inject the required types of materials into the aquifer, in-situ immobilization was eliminated from further consideration for groundwater remediation.

2.2.4 In-Situ Treatment

In-situ treatment consists of technologies that treat the groundwater in place and generally remove or break down the contaminant in some form. The main advantage of in-situ treatment is that the groundwater could be treated without being brought to the surface, which could result in large cost savings. The main disadvantages of these technologies are usually a longer treatment period and difficulty in verifying how well the process is working, especially in aquifers with a nonuniform environment. The in-situ treatment technologies considered for this analysis include bioremediation, electrokinetics, reactive walls, air stripping, Fenton-like reagents, and phytoremediation.

2.2.4.1 Bioremediation

In-situ bioremediation involves the use of microorganisms to degrade hazardous chemicals such as organics and nitrates into smaller, less hazardous chemicals (toxicity reduction). Such an approach is not applicable to uranium in groundwater, although biosorption can be used to remove uranium from groundwater in an ex-situ process (see Section 2.2.6). Traditional in-situ groundwater bioremediation systems generally involve a series of injection wells or trenches to introduce oxygenated, nutrient-rich water to the contaminated aquifer; water recovery is performed by another series of wells downgradient of the contamination. The recovered water must also be treated and then discharged, either back into the aquifer if local regulations permit, to surface water, or to a local sanitary water treatment plant.

The biodegradation of TCE is a well-known phenomenon and has been shown to occur under anaerobic conditions in both the laboratory and the field and under aerobic conditions in the laboratory (see Section 2.2.2). This process could also occur under aerobic conditions in the field (McCarty 1994). Biodegradation of nitroaromatic compounds has been extensively studied (Section 2.2.2); however, in-situ treatment is not recommended because of the potential mobility of intermediates and other difficulties such as delivery problems with nutrient sources (EPA 1993). For biodegradation of nitrates, the anaerobic nature of most aquifers favors denitrification because oxygen competes with nitrate as an electron acceptor in the metabolism of microorganisms (Hiscock et al. 1991). However, as for TCE and nitroaromatic compounds, biodegradation of nitrates requires a source of oxidizable carbon to sustain the microorganisms.

Bioremediation of groundwater could be implemented only in limited areas at the WSCP because of the difficulty of injecting material (microorganisms and their feed) into the aquifer (Section 2.2.3) because of the low permeability of the aquifer. In addition, the heterogeneous nature of the aquifer in these areas precludes the uniform delivery of this material, thus making implementability highly questionable.

The screening analysis for in-situ treatment is summarized in Table 2.2. On the basis of implementability, bioremediation was rejected from further consideration at the WSCP and WSOW because of the inability to inject materials into the aquifer.

2.2.4.2 Electrokinetics

Technologies involving electrokinetics rely on the transport phenomena associated with the application of a voltage between implanted electrodes in porous media. These phenomena include electrophoresis (movement of a charged particle or colloid in an electric field), electromigration (movement of solute ions in an electric field), and electroosmosis (movement of water in response to an electric field). Once the contaminants reach an electrode, they can be extracted to a recovery system (ex-situ treatment), treated in a reaction zone surrounding the electrode, or deposited (precipitated, adsorbed, or electroplated) at the electrode. Electrokinetics is potentially applicable for treating TCE, nitrates, and uranium (Acar 1993; Trombly 1994; EPA 1995a; Van Cauwenberghe 1997) found at the WSCP and WSOW.

The feasibility of using electrokinetics at the WSCP and WSOW is uncertain because of the relative newness of the technology, the depth of contamination, and the presence of contamination in both overburden and bedrock. The application of electrokinetics to full-scale remediation of nitrate or uranium-contaminated sites is not established. For TCE, a limited field test has been conducted successfully in unsaturated soil (Shannon 1995). However, the use of electrokinetics to treat the TCE-contaminated area in the saturated zone near raffinate pits 3 and 4 is highly uncertain. Contamination is present in both the overburden and the bedrock at depths exceeding 15 m (50 ft). Also, extensive research and development would be required before electrokinetics could be applied to the TCE-contaminated area in order to optimize the removal process, because of the technology's dependence on several compositional (chemical makeup) and environmental (e.g., water content, soil homogeneity) variables. Currently, no full-scale site remediation of TCE, nitroaromatic compounds, nitrates, or uranium using electrokinetics has been reported in the United States.

The screening analysis for in-situ treatment is summarized in Table 2.2. Electrokinetics has been rejected as potentially applicable to remediating the TCE contamination at the WSCP because its effectiveness and implementability in groundwater have not yet been demonstrated.

2.2.4.3 Reactive Walls

A technological alternative to erecting a physical barrier to halt contaminated groundwater migration (Section 2.2.3.1) would be the use of a reactive chemical wall. Barrier walls could be

sampling frequency would be determined in collaboration with the regulators. (Response measures might be considered if data indicated that future migration of contamination would result in unacceptable off-site exposure. Contingency measures to prevent exposure to contaminated groundwater could include developing an alternative water supply for the public [which could be provided by a wide range of actions, such as well relocation, selective use of wells, or connection to an existing system or surface water source], well head treatment, and use restrictions.)

3.3.2.3 Alternative 3: Natural Attenuation

Natural attenuation is defined in the NCP as "biodegradation, dispersion, dilution, and adsorption" of contaminants in groundwater. The NCP preamble states that natural attenuation is generally recommended when active restoration is not practicable, cost effective, or warranted on the basis of site-specific conditions (e.g., where groundwater is not a likely source of drinking water) or when natural attenuation could achieve remedial goals in a reasonable time frame. Natural attenuation may be a useful remedial approach if site-specific data indicate that these processes would effectively reduce contaminants in the groundwater to concentrations protective of human health and the environment in a time frame comparable to that which could be achieved through active remediation (EPA 1988b).

Natural attenuation relies on natural subsurface processes to reduce contaminant concentrations to acceptable levels. Such processes include dilution, volatilization, biodegradation, adsorption, chemical reactions with subsurface materials, and radioactive decay. Further information on natural attenuation is provided in Section 2.2.2. Natural attenuation has been stated to have many advantages over conventional engineering remediation alternatives (Goffredi 1997b), including the following:

- Contaminants are ultimately transformed into innocuous by-products (such as CO_2, ethylene, ethane, Cl^-, and water for TCE) and not just transferred to another phase or location in the environment;
- Attenuation allows use of the existing infrastructure at a site during remediation;

- Contaminants are generally not transferred to the atmosphere, which prevents increased risk to nearby populations and the environment.
- Attenuation is less expensive than currently available remediation technologies such as conventional extraction and ex-situ treatment ("pump and treat");
- No equipment downtime or maintenance is involved;
- The most mobile and toxic organic compounds are usually the most susceptible to biodegradation.

Hydrogeologic constraints can limit the effectiveness of active restoration when plumes migrate into formations from which they cannot easily be removed; in these special situations, natural attenuation with monitoring and institutional controls has been identified as potentially being the only feasible remedy (EPA 1988b). Such situations include sites with contaminant migration into formations with a high degree of secondary permeability, such as fractured bedrock or karst aquifers. For comparative purposes, the shallow bedrock aquifer system, which contains the majority of the groundwater contamination, has been conceptualized to be a diffuse flow system where the bedrock is thinly bedded or fractured sufficiently to serve as a uniform porous medium; superimposed conduit flow occurs in large isolated fractures. These conditions indicate that a karst hydrologic system is in operation in the bedrock beneath and around the site; this suggests that it may not be practicable or feasible to fully restore groundwater by active remediation.

The conditions potentially favoring the use of natural attenuation are as follows (EPA 1988a): groundwater naturally unsuitable for consumption, low-mobility contaminants, low concentrations of contaminants, low potential for exposure, and low projected demand for future use of the groundwater. These conditions may be compared with the prevailing conditions at the WSCP and the WSOW, as follows:

- ***Groundwater Naturally Unsuitable for Consumption:*** Groundwater that is naturally unsuitable for consumption includes groundwater that is saline (total dissolved solids levels over 10,000 mg/L) or groundwater that is not available in sufficient quantity at any depth to meet the needs of an average household. Existing data suggest that long-term sustainable pumping rates are very low,

erected that would funnel the flowing groundwater into treatment zones where the contaminant(s) would be extracted. Another variation of the reactive wall concept would be construction of a wall filled with material having an affinity for the contaminant, either one of sorption or reaction (precipitation or degradation). With this method, the contaminant is preferentially removed from the groundwater as the groundwater passes through this more passive chemical wall (permeable treatment wall) during natural migration through the aquifer.

The use of a reactive wall with treatment zones to extract contaminants is not warranted, because these zones would have to be maintained indefinitely to treat small amounts of groundwater with low levels of contamination until the contaminant concentrations decreased below levels of concern. The alternative — a passive, permeable chemical wall — could be constructed, left to filter the groundwater, and monitored periodically. If the wall material were to reach saturation levels with the contaminant, the existing barrier could be excavated, disposed of, and replaced with fresh material. Field tests or commercial applications of permeable walls have already been employed to treat groundwater for TCE, nitrates, and uranium (Vidic and Pohland 1996). Also, some natural clays have been shown to have good adsorption properties for nitroaromatic compounds such as TNT (Haderlein et al. 1996; Weissmahr et al. 1997). Such an effort would require further characterization of the chemical systems operating in the aquifer, and, like the physical barrier discussed in Section 2.2.3, the reactive wall would need to be maintained indefinitely.

Placing long reactive walls to treat the contamination found over the entire WSOW and WSCP areas is impractical. For localized applications, the major obstacles to the use of a reactive wall at the WSCP and WSOW are the same as those for a barrier wall: depth of contamination in the aquifer, installation in bedrock, and presence of natural groundwater conduits. Therefore, reactive walls were rejected from further consideration as an in-situ treatment technology, as summarized in Table 2.2.

2.2.4.4 Air Stripping

In-situ air stripping (also known as in-well vapor stripping or in-situ vapor stripping) is a potential technology for the removal of TCE from the groundwater at the southwest corner of the WSCP. A typical setup (Miller and Roote 1997) involves a well that has upper and lower screened intervals. Air is injected from the surface into a region near the lower screen inside the well, resulting

in an upward flow within the well because of the decreased density of the groundwater. As the air bubbles rise, VOCs such as TCE transfer from the dissolved to the vapor phase. The upper screen is situated just below or above the top of the contaminated aquifer where the less-contaminated groundwater exits the well back into the aquifer. The contaminated air discharged at the top of the well is vacuum extracted for VOC vapor treatment. This arrangement results in a recirculating pattern of groundwater around each well; water enters at the bottom and exits at the top. One commercial application of this technology is the NoVOCs™ process (Miller and Roote 1997). Air injection also has the added potential for enhancing any aerobic biological degradation processes in an aquifer.

The TCE plume near the raffinate pits at the WSCP might be amenable to remediation with in-situ air stripping because of the permeability of the groundwater aquifer. The plume is located near one of the regions of highest permeability in the area; the hydraulic conductivity is in the 10^{-3} to 10^{-2} cm/s range (MK-Ferguson Company and Jacobs Engineering Group 1990a). Some of the TCE lies within the Burlington-Keokuk Limestone formation, which is highly fractured in the upper weathered portion; the horizontal fractures along the bedding planes dominate the vertical fractures by a ratio of about 20:1 (DOE and DA 1998b). This situation suggests that a recirculation pattern around an air stripping well might not be able to be established and that the water discharged at the top of the well would actually push contaminated water away from the well through the horizontal fractures because the groundwater's travel in the vertical direction is more limited. .

Because of the potential effectiveness of air-stripping in removing the TCE, this technology has been retained for further consideration, as summarized in Table 2.2. However, a field test of this technology would be required before full-scale implementation, because of the uncertainties related to the aquifer's permeability and the horizontal-to-vertical flow ratio.

2.2.4.5 Fenton-Like Reagents

Another potential technology for remediating TCE contamination at the WSCP is a Fenton-like process. The general process involves the introduction of Fenton's reagent, hydrogen peroxide (H_2O_2), and ferrous iron (Fe^{2+}), such as iron sulfate ($FeSO_4$), into an aquifer with organic contamination. Reaction of H_2O_2 with $FeSO_4$ produces hydroxyl radicals, which are strong oxidants. The hydroxyl radicals in turn react with most organic contaminants at rates close to the theoretical

limit, which is controlled by the diffusion rate in water. The advantages of such a technology include the potential full mineralization of TCE to form oxygen, carbon dioxide, and chloride ions (O_2, CO_2, and Cl^-); the potential application to remediating the nitroaromatic contamination; and the ability of the H_2O_2 to follow the TCE in the aquifer because both are heavier than water.

The use of Fenton's reagent for groundwater remediation of organic compounds is relatively new. Application to TNT and 2,4-DNT groundwater remediation has been limited to lab-scale testing (Mohanty and Wei 1993; Li et al. 1997). Laboratory studies (Gates and Siegrist 1995), in-situ field tests for degradation of TCE contamination in groundwater (Andrews et al. 1997; Pucik et al. 1997), and site remediation (Vigneri 1996) have shown promising results.

However, a number of potential problems are related to the application of Fenton's reagent technology to the TCE-contaminated aquifer (or other areas with nitroaromatic contamination) at the WSCP and the WSOW. Thorough mixing of the Fenton's reagent with the contaminated groundwater (uniform delivery) is necessary for effective remediation (Venkatadri and Peters 1993). Such a condition is not possible in the WSOW and the WSCP because of the karst nature of the aquifer and the variability in the hydraulic conductivity, which is approximately 10^{-5} cm/s or less over most of the area. The low permeability of these areas is itself a problem (Vigneri 1996). It limits the degree of penetration of Fenton's reagent beyond the injection well due to decomposition of the H_2O_2. In the case of low permeability, the use of added stabilizers to retard the decomposition of the H_2O_2 is not expected to provide much benefit (Kakarla and Watts 1997).

The hydraulic conductivity is as high as approximately 10^{-2} cm/s in the TCE-contaminated portion of the aquifer. However, the variability of the permeability in this area (down to a hydraulic conductivity of approximately 10^{-6} cm/s near monitoring well MWS-21) and the karst conditions would again cause problems with uniform delivery. The permeability of this region could also be lowered due to the precipitation of oxidized iron compounds that result from the Fenton process (Venkatadri and Peters 1993), which could possibly cause clogging of the injection wells. The Fenton process is most effective in water with a pH between approximately 2 and 4 (Venkatadri and Peters 1993), which presents another potential problem. Lowering the pH of the groundwater can have unexpected effects and may not be reasonably achievable if the limestone aquifer has a large buffering capacity.

The screening analysis for in-situ treatment is summarized in Table 2.2. The use of Fenton-like reagents was rejected as potentially applicable to remediation of the TCE-contaminated groundwater at the WSCP because of problems associated with nonuniform delivery of the reagents and potential adverse chemical reactions.

2.2.4.6 Phytoremediation

Phytoremediation is a recently recognized technology that uses vegetation (plants) to extract contaminants from soil and groundwater in-situ. The process can be applied to metals contamination through extraction or stabilization. Organic compounds are remediated through degradation or extraction. Application of phytoremediation is dependent upon the depth of contamination and the selection of plant species appropriate to the contamination, cleanup standard, and climate.

One aspect of phytoremediation is exploitation of the enhanced microbial populations that coexist with a plant's root system (the rhizosphere). Within the rhizosphere, plants contribute the carbonaceous substrate and oxygen transfer for in-situ biodegradation. Rhizodeposition is partially the result of the decay of dead roots and root hairs. Also important to the process are root exudations, such as leakage from epidermic cells, secretions resulting from metabolic activity, mucilage from root tips, and lysates from sloughed cells. This resultant carbonaceous material stimulates overall bacterial activity and provides substrate for cometabolic degradation of xenobiotic hydrocarbons.

The dominant active mechanism for phytoremediation of metals such as uranium is phyto-extraction into the tissue of the plant (Cornish et al. 1995; Cooney 1996). Plant enzymes are responsible for the degradation of TNT (Schnoor et al. 1995), which may be degraded either in the rhizosphere or after uptake by the plant (Hughes et al. 1997). For some organics such as TCE, some of the organic contaminants may be transpired to the atmosphere before complete degradation in the plant following phytoextraction (Gordon et al. 1996). The mechanism for metal accumulation includes chelation, precipitation, compartmentalization, and translocation. To successfully apply this technology to a site contaminated with metals, the pH, organic complexes, and interfering elements must be assessed, and the plant species used must have the appropriate metal selectivity. In some instances, it may be necessary to apply soil amendments to enhance the process.

Application of phytoremediation for removing TCE, nitroaromatic compounds, nitrates, and uranium is promising. However, a depth limitation of approximately 3 m (10 ft) (Miller 1996a)

precludes its use for remediation of the groundwater at the WSCP and the WSOW because contamination has been detected at depths of 15 m (50 ft) or more at some locations. Other issues also need resolution, such as the relatively long times necessary to reach remediation goals, subsequent handling and disposition of accumulated biomass, securing plants from other bioaccumulators (wild fauna), and introduction of nonnative plants for phytoremediation (Negri and Hinchman 1996).

The screening analysis for in-situ treatment is summarized in Table 2.2. Phytoremediation was rejected as a remediation technology on the basis of implementability (the technology is limited to an effective depth of about 3 m [10 ft]).

2.2.5 Removal of Groundwater from the Aquifer

Remediation of groundwater with ex-situ treatment requires that the contaminated groundwater first be extracted from the aquifer. The groundwater removal technologies investigated for the WSCP and the WSOW included the use of vertical wells, horizontal wells, interceptor drains, and excavation.

2.2.5.1 Vertical Wells

The use of vertical wells is most common in pump-and-treat technologies for groundwater remediation. However, the low permeability of the aquifer at the WSOW and a large portion of the WSCP with hydraulic conductivities on the order of 10^{-5} cm/s or less precludes the use of such wells. Well yields are typically about 4 L/min (1 gpm) or less at the WSCP (MK-Ferguson Company and Jacobs Engineering Group 1990a). A significant increase in pumping capacity, as much as a factor of 100, has been observed at other remediation sites where fracturing of the surrounding consolidated aquifer material was carried out (Miller 1996b). Such a technology uses hydro-, pneumatic-, or blast-fracturing methods applied to bedrock material. Most other materials only deform under such treatment, and pumping capacity is not improved.

The use of vertical wells for groundwater extraction at the WSCP may be feasible without fracturing because of the higher permeability of the groundwater aquifer in the vicinity of the raffinate pits and well MW-2009, where the hydraulic conductivity is on the order of 10^{-3} to 10^{-2} cm/s. Fracturing methods in the TCE-contaminated area near the raffinate pits should be used with caution because any vertical fractures might allow TCE to penetrate deeper into the bedrock.

Since the TCE contamination does not exist as a DNAPL at the site, its migration downward into any induced fractures will be slow, because it is dissolved in the groundwater and is expected to be captured at the start of pumping operations. Confining the fracturing operations to the contaminated layers will also reduce the risk of contaminating underlying layers. However, there is concern that fracturing operations would be detrimental to the integrity of the nearby disposal cell that is already under construction at the WSCP.

Also of concern is the potential effectiveness of using vertical wells to capture any contaminant, because of the karst nature of the contaminated aquifer at the WSOW and the WSCP (Mugel 1997). Accounting for and containing all preferential flow conduits is impractical. Small, unknown flow channels can severely compromise the effectiveness of a single vertical well, which in turn limits the effectiveness of the entire pump-and-treat network.

The screening analysis for removal of groundwater from the aquifer is summarized in Table 2.3. Vertical wells have been retained as potentially applicable to removing groundwater in limited areas at the WSCP where the permeability of the aquifer is highest.

2.2.5.2 Horizontal Wells

The use of horizontal wells is a more advanced technology than the use of vertical wells. Horizontal wells could be drilled through the aquifer in an effort to increase the area available for pumping the groundwater. Two methods commonly used to position the wells are directional drilling and trenching. Excavating a trench and partially backfilling it with porous material over a horizontal well pipe can increase the pumping capacity of a well and is similar in concept to fracturing of the aquifer around the well intake. However, excavating trenches for this application is not feasible because contaminated locations at the WSCP and the WSOW often have contamination down to an approximate depth of 15 m (50 ft) into bedrock. Directional drilling is capable of going through bedrock and might be feasible for installing horizontal wells at the WSCP and the WSOW.

The screening analysis for removal of groundwater from the aquifer is summarized in Table 2.3. Horizontal wells have been retained as potentially applicable to removing groundwater in regions of higher permeability at the WSCP.

TABLE 2.3 Summary of Screening Analysis for Groundwater Removal

Removal Measure	Effectiveness	Implementability	Cost
Vertical wells	Standard method for removing groundwater from an underground aquifer.	Very difficult to implement. The low permeability of the aquifer precludes reasonable pump rates, except for possible locations at the WSCP. Pump rates might be increased by fracturing of the bedrock.	Low to moderate
Horizontal wells	Larger surface area available for collecting groundwater than a conventional vertical well, which results in higher pump rates.	Very difficult to implement. The low permeability of the aquifer might preclude reasonable pump rates. Pump rates might be increased by fracturing of the bedrock.	Moderate
Interceptor drain	A trench placed downgradient of the contamination on both sides of the groundwater divide could intercept all contaminated groundwater leaving the area. The groundwater that collected in the trench could then be pumped out for treatment.	Could not be implemented with conventional methods and equipment in a bedrock aquifer.	Moderate
Excavation/dredging and pumping	Could effectively remove contaminated material in the aquifer. The original sources of groundwater contamination have been removed or are in the process of being removed. The contaminant concentrations in the aquifer material are expected to be low.	Could not be implemented with conventional equipment and procedures in a bedrock aquifer.	High

2.2.5.3 Interceptor Drains

A technology employing an interceptor trench drain could be used to further increase groundwater recovery. A trench placed perpendicular to the groundwater flow would intercept the contaminated groundwater. The trench could be backfilled with porous material so that the entire side of the trench would act as a sink for the groundwater, which would be pumped to a treatment facility. The advantage of a trench, when properly positioned, is its simplicity and effectiveness, thus ensuring that any contaminated water would be intercepted. Implementation of a remediation strategy using an interceptor trench has similar problems to those discussed for barrier walls (Section 2.2.3.1) and reactive walls (Section 2.2.4.3) for a broad or local implementation. It would be impractical to construct two trenches (one on each side of the groundwater divide), each one approximately 5 km (3 mi) long, to encompass all of the contamination, which is widely scattered and at relatively low

levels in most locations. Implementation of an interceptor drain on a smaller scale for containing areas of higher contamination is not feasible because contaminants have been detected at depths to at least 15 m (50 ft) in bedrock at both the WSCP and the WSOW. Thus, the interceptor drain technology for groundwater removal was rejected, as shown in Table 2.3.

2.2.5.4 Excavation

Because of the low permeability of the aquifer at the WSOW and a large portion of the WSCP (hydraulic conductivity $\leq 10^{-5}$ cm/s), an alternative to pumping or draining the contaminated groundwater from the aquifer would be to excavate the aquifer material for treatment and disposal. Conventional earthmoving equipment (e.g., bulldozers, backhoes, and front-end loaders) would be used in conjunction with hydraulic dredges and pumps. Any uncontaminated overlying soil could be stripped off and replaced after removal of the underlying contaminated aquifer material. However, because the contamination is so widespread and the contaminant concentrations relatively low, little would be gained by excavating the aquifer material itself. Also, the contaminant sources have been or are in the process of being removed. In addition, it would be impractical to excavate such large volumes and any of the bedrock with contaminated groundwater.

The screening analysis for removal of groundwater is summarized in Table 2.3. Excavation was rejected from further consideration on the basis of the low contaminant concentrations in the aquifer material and implementability (i.e., the large volume of material and difficulty in removing bedrock).

2.2.6 Ex-Situ Treatment

Ex-situ treatment consists of technologies that treat the groundwater and any contaminated soil or sludge after removal from the aquifer. The many methods available for treating contaminated groundwater rely on the physical, chemical, or biological properties of the contaminants.

2.2.6.1 Physical Methods

Settling or Centrifuge. Settling (sedimentation) tanks for removal of suspended solids constitute one of the first stages of many water treatment plants. Settling tanks allow these

nondissolved solids (approximately 10 μm in diameter or larger) to settle to the bottom of the tank under the influence of gravity. After an appropriate time period, the clarified water may then be drawn off and sent on to the next phase of treatment. Centrifuges may also be used to remove suspended particles from solution. In addition, settling tanks may be used in conjunction with chemical precipitation treatments.

Filtration. Filtration is another process found in many water treatment plants. Like settling, filtration is used for removing suspended solids. Filters may consist of a single thin membrane (typically a polycarbonate) or a granular medium (typically sand in a filter bed). The driving force is either gravity or a pressure differential such as applied pressure or an induced vacuum. Filtration is relatively simple to operate and maintain, and like settling, filtration is an old and proven technology. Filtration is often used in conjunction with chemical precipitation processes.

Evaporation. Evaporation is used primarily for reducing the volume of contaminated water or sludge wastes and for concentrating nonvolatile contaminants such as nitroaromatic compounds, nitrates, and uranium. Any volatile contaminants such as TCE must be removed prior to this treatment process. Evaporation of water leaves behind all nondissolved and dissolved solids. The treated waste must then be mechanically removed for further treatment or disposal. Evaporation ponds are often used as retention areas for treated wastewater in between treatment steps. Evaporation is a well-established treatment process.

Reverse Osmosis. Reverse osmosis is commonly used to remove dissolved species from solution. Osmosis is the tendency of a solvent such as water to pass through a semipermeable membrane from the side with a lower solute (dissolved species) concentration to the side with a higher solute concentration in an attempt to equalize concentrations on both sides of the membrane. The membrane is semipermeable in that it permits migration of water but not the dissolved species. This process may be reversed, hence the term reverse osmosis, by applying pressure to the side with a high solute concentration. The dissolved species thus become more concentrated, thereby reducing the volume of contaminated water. Reverse osmosis is very effective at removing almost all dissolved species. This process is an established method often used for treating water contaminated with nitrates (Canter 1997; Kapoor and Viraraghavan 1997) or uranium.

Summary. The screening analysis for ex-situ treatment of groundwater is summarized in Table 2.4. All physical treatment technologies were retained for possible use in conjunction with groundwater extraction.

2.2.6.2 Chemical Methods

Coagulation/Flocculation. Coagulation is a chemical treatment process in which chemicals are added to promote particle growth under flocculation, a physical process that increases particle collisions through slow mixing with large blades or paddles. Coagulation/flocculation is often used in conjunction with precipitation processes or as a component in a settling or filtration treatment stage.

Precipitation. Precipitation of inorganic contaminants in water is induced by a chemical reaction that converts a soluble contaminant species to an insoluble form. Removal of the precipitate is then accomplished through sedimentation or filtration. One advantage of precipitation treatments is the relatively low waste volumes produced. Because of the diverse chemical species found in groundwater, selection of the proper chemicals for use generally requires bench and field studies that often include pH adjustment for optimum results. Precipitation is an effective and well-established treatment for many contaminants and has been a primary treatment for metals in industrial waste waters for years (DOD 1994). Lime softening is one precipitation process that has an efficiency of approximately 85 to 99% for removal of dissolved uranium (EPA 1993).

Ion Exchange. Ion exchange is a process in which ions of interest are exchanged for other ions held on an insoluble exchange material. The exchange material is generally a synthetic organic resin that is stable under a wide range of temperature and pH conditions. These materials can be tailored to be highly specific toward a given ion. Once a resin becomes saturated with the target ion, the resin can be regenerated using a highly concentrated solution of the relatively harmless, originally bound ion. This solution shifts the equilibrium back to the original state of the resin and leaves a solution concentrated in the target (contaminant) ion. Ion exchange is a well-established treatment for many contaminants and is widely used for the treatment of nitrates (Canter 1997) and uranium (DOE 1991).

TABLE 2.4 Summary of Screening Analysis for Ex-Situ Treatment Measures

Ex-Situ Measure	Effectiveness	Implementability	Cost
Filter	Preliminary step to separate suspended solids from the extracted groundwater.	Easy to implement with existing water treatment technology.	Low
Coagulation/ flocculation	Used to enhance filtration and settling processes.	Easy to implement.	Low
Settling/centrifugation (clarification)	Preliminary step to separate suspended solids from the extracted groundwater.	Easy to implement.	Low
Evaporation	Consolidates suspended and dissolved solids by driving off the water. The resulting contaminated solid can be sent for disposal.	Easy to implement.	Low
Reverse osmosis	Potential preliminary step for treatment. Effective at concentrating dissolved contaminants in solution.	Could be implemented with existing technology.	Moderate
Coprecipitation	Conventional method for extracting uranium from solution. Dependent on dissolved species.	Could be implemented with existing technology.	Moderate
Ion exchange	Conventional method for extracting uranium and nitrates from solution. Dependent on dissolved species.	Could be implemented with existing technology.	Moderate
Liquid-liquid extraction	Conventional method for extracting uranium from solution. Dependent on dissolved species.	Could be implemented with existing technology.	Moderate
Supported liquid membranes	Newer technology for extracting dissolved metals; being investigated for remediation programs.	Implementation questionable.	High
Magnetic separation	Newer technology for extracting dissolved metals; being investigated for remediation programs.	Implementation questionable.	High
Ultraviolet oxidation	Conventional method for degradation of nitroaromatic compounds and TCE.	Could be implemented with existing technology.	Moderate
Granular activated carbon	Conventional method for extracting TCE from vapor and for extracting TCE and nitro-aromatic compounds from solution.	Could be implemented with existing technology.	Moderate
Biosorption	Newer technology under development for extracting dissolved metals; being investigated for remediation programs.	Implementation questionable.	High

TABLE 2.4 (Cont.)

Ex-Situ Measure	Effectiveness	Implementability	Cost
Biodegradation	Newer technology under development for degradation of TCE, nitroaromatic compounds, and nitrates by microorganisms; being investigated for remediation programs.	Implementation questionable.	High
Electrodialysis	Effective at extracting nitrates from drinking water.	Could be implemented with existing technology.	High
Enzyme-catalyzed reduction	Newer technology under development for extracting nitrates from drinking water.	Implementation questionable.	High
Phytoremediation	Constructed wetlands could remove/degrade TCE, nitroaromatic compounds, nitrates, and uranium from extracted groundwater.	Could be implemented with existing technology.	Low
Incineration	Supporting measure. Conventional method for destruction of organic compounds and waste volume reduction.	Could be implemented with existing technology.	Moderate

Liquid-liquid extraction. Liquid-liquid extraction involves the complexation of an inorganic species such as a dissolved uranium ion with an organic compound. The contaminated aqueous solution is then mixed with an organic solvent that is not soluble in water. The complexed species is designed to be more soluble in the organic solvent than water, and, therefore, is preferentially extracted into the organic liquid phase, which is subsequently drawn off from the aqueous phase. This method can be highly selective toward a single contaminant in a complex solution. Liquid-liquid extraction has been used extensively in the nuclear industry for the processing of spent nuclear fuel for the separation of uranium and plutonium (Ivanovich and Harmon 1992). However, the involvement of an organic liquid phase, often a hazardous chemical itself, relegates this method to operations where other methods have proven ineffective.

Magnetic Separation. Two different types of magnetic separation processes have recently been investigated for the remediation of contaminated groundwater — the Mag*Sep^{SM} and high-gradient magnetic separation (HGMS).

The Mag*Sep^{SM} process injects engineered particles into a liquid waste stream. The particles range in size from 25 to 300 μm, have a magnetic core, and are coated with a functionalized

resin. The resin acts in a manner similar to ion-exchange resins; that is, they adsorb selective target ions. After the particles have been in the contaminated water for an appropriate period of time, they are magnetically removed from solution (DOE 1996b). The process is claimed to be more selective than ion exchange and, therefore, produces less waste product. No full-scale commercial applications of this process have been conducted for remediation of uranium in groundwater.

The HGMS process passes the contaminated fluid through a highly magnetized volume containing a magnetic matrix material such as steel wool. A slightly magnetic contaminant species such as uranium becomes attached to the matrix material and is then removed from solution. The process results in very small waste volumes. Application of this technology to water treatment is still in the research phase at Los Alamos National Laboratory.

Supported Liquid Membranes. A liquid membrane containing a complexing agent for a specific contaminant such as uranium is supported on a hollow fiber membrane through which a liquid waste stream is passed. The complexing agent attaches to its target ion when the ion contacts the liquid membrane. The contaminant ion complex is then selectively passed through the membrane where it comes into contact with a stripping solution. Supported liquid membranes have been studied for over 20 years for a variety of applications and more recently for the removal of uranium, chromium, and technetium from contaminated groundwaters (DOE 1995). The interest in the process is related to its high target specificity, which results in reduced waste volumes. Also, the recovered contaminant, such as uranium, would be in a reasonably pure form for potential reuse. However, no field tests have been reported.

Ultraviolet Oxidation. Ultraviolet (UV) oxidation is a treatment process for organic compounds and is effective in the treatment of nitroaromatic compounds (DOD 1994). Its primary advantage over other methods such as carbon adsorption is its destruction of the contaminant compounds; it is capable of complete mineralization to carbon dioxide, water, and salts. The process involves exposing the contaminated water to strong UV light in the presence of strong chemical oxidizers such as ozone and/or hydrogen peroxide. UV oxidation is an established treatment process and is readily available from commercial vendors.

Granular Activated Carbon. Carbon adsorption is very effective in treating organically contaminated waste waters. Granular activated carbon (GAC) has a high surface area and has been used extensively in treating process waters at munitions plants (EPA 1993). This process involves the adsorption of organic contaminants on carbon surfaces as the waste water is passed through a GAC filter. Therefore, the contaminants are not destroyed, and the GAC in the filter must be further treated or disposed of. Carbon adsorption is readily available from commercial vendors since it is a well-established technology for treating municipal, industrial, and hazardous wastes.

Incineration. Incineration is not directly applicable to groundwater treatment but can be used to treat secondary waste products. The incineration of hazardous wastes is an effective technology for destruction of organic contaminants and can also be used for volume reduction of combustible wastes contaminated with inorganic contaminants. Furnace temperatures typically range from 870 to 1,200°C (1,400 to 2,200°F). Incineration has been used for the destruction of nitroaromatic compounds in contaminated soils (EPA 1993). The technology is readily available from commercial vendors.

Electrodialysis. Electrodialysis uses a direct electric current to transport ions through semi-permeable membranes from solutions of low to high concentrations (Canter 1997; Kapoor and Viraraghavan 1997). Pretreatment of the water (e.g., filtration) is generally necessary to avoid fouling the membranes. The efficiency for the removal of nitrate from solution is comparable to that for reverse osmosis.

Enzyme-Catalyzed Reduction. The reduction of nitrate by enzymes to nitrogen has the advantage of destroying the contaminant rather than concentrating it as occurs in other physical/chemical processes such as ion exchange, reverse osmosis, or electrodialysis. While biodegradation of nitrate also destroys the nitrate, enzyme-catalyzed reduction does not have the problem of maintaining cultures of microorganisms.

Summary. The screening analysis for ex-situ treatment of groundwater is summarized in Table 2.4. All chemical treatment technologies, except the supported liquid membrane and magnetic separation technologies for uranium, were retained for possible use in conjunction with groundwater

extraction. Determination of the appropriate technologies would depend on the chemical characteristics of the groundwater at the time of extraction. Enzyme-catalyzed reduction and electrodialysis were not retained for consideration for nitrate removal. Enzyme-catalyzed reduction is still a developmental technology, and electrodialysis is useful only for treating soft water and has high operating costs (Kapoor and Viraraghavan 1997). Ion exchange was retained for nitrate removal because it is an established process and is used at the quarry water treatment plant.

2.2.6.3 Biological Methods

Biological treatment technologies involving microbial degradation are available for TCE, nitroaromatic compounds, nitrates, and uranium. The organic contaminants and nitrates can be broken down into less hazardous constituents by certain microorganisms (see Section 2.2.2). Uranium can be scavenged by certain bacteria that in turn can be scavenged from the water. These remedial technologies are still in various stages of development, except for biological denitrification, which has been developed over the years to treat domestic wastewater (Canter 1997; Kapoor and Viraraghavan 1997). However, domestic wastewater generally has a high organic content that provides nutrients for the microorganisms, whereas most groundwater aquifers such as that at the WSCP and WSOW have low organic content. Development of an appropriate bioreactor to treat nitrates in groundwater at the WSCP and WSOW would be required.

Phytoremediation is a biological technology that can be used as an ex-situ method (see Section 2.2.4.6). Irrigation of a constructed wetlands can be used to remove the contaminants by filtering the extracted groundwater. Advantages over other methods include lower cost, destruction of the contaminant (except for uranium), and lower final waste volumes.

No biological methods involving microbial degradation were retained for ex-situ groundwater treatment, as summarized in Table 2.4, because of their developmental nature and the lack of clear advantages over physical and chemical methods. Phytoremediation was retained for future consideration as an ex-situ treatment technology.

2.2.7 Disposal

The disposal option supports other groundwater response actions. This option is limited to disposal of the by-products of other response actions. All solid contaminated waste resulting from

groundwater remediation would be sent to an off-site facility. Uncontaminated solid process waste could be disposed of off-site at a commercial facility, as appropriate. The treated groundwater could be discharged to the Missouri River or used for landscape irrigation.

2.3 POTENTIALLY APPLICABLE TECHNOLOGIES

Potentially applicable technologies for groundwater remediation are summarized in Table 2.5. This summary is based on the screening analysis presented in Section 2.2. The technologies that have been retained through this analysis were used to develop preliminary remedial action alternatives for the site. These alternatives are identified in Chapter 3.

TABLE 2.5 Screening of Potentially Applicable Technologies for Groundwater Remediation

General Response Action	Technology Type	Evaluation Result	Comments
Institutional controls	Groundwater access restrictions	Retained	Could effectively limit access to areas with contaminated groundwater. Could be used to support other response actions.
	Ownership and land use or deed restrictions	Retained	Could minimize exposures to site contaminants by limiting use of contaminated groundwater areas. Could be used to support other response actions.
Monitoring	Vertical wells	Retained	Could provide data useful for minimizing exposures. Could be used to support other response actions.
In-situ containment	Physical barrier	Rejected	Difficult to install barrier walls in bedrock and difficult to control groundwater flow that can occur in natural conduits.
	Hydraulic containment	Rejected	Low permeability and preferential flow conduits in the aquifer would limit effectiveness.
	Immobilization	Rejected	Could not inject required material into the aquifer because of the aquifer's low permeability.
In-situ treatment	Natural processes	Retained	Could reduce contaminant concentrations given sufficient time. Could be used to support other response actions.
	Bioremediation	Rejected	Could not inject required material into the aquifer because of the aquifer's low permeability.
	Electrokinetics	Rejected	Application to full-scale remediation for the contaminants of concern has not yet been demonstrated.
	Reactive wall	Rejected	Difficult to install long barrier walls in bedrock and difficult to control groundwater flow that can occur in natural conduits.
	Air stripping	Retained	For limited use at the WSCP to treat the TCE contamination.
	Fenton oxidation	Rejected	Low and nonuniform permeability of the aquifer limits its effectiveness in remediating organic contaminants.
	Phytoremediation	Rejected	Ineffective at remediating contamination that is more than about 3 m (10 ft) deep.
Removal	Vertical wells	Retained	For limited use at the WSCP where the aquifer's permeability might be high enough for reasonable pump rates.
	Horizontal wells	Retained	For limited use at the WSCP where the aquifer's permeability might be high enough for reasonable pump rates.
	Interceptor drain	Rejected	Difficult to install trenches in bedrock and difficult to control groundwater flow that can occur in natural conduits.
	Excavating/dredging and pumping	Rejected	Sources of contamination have already been removed or are in the process of being removed. Concentrations of remaining contaminants in the aquifer material are expected to be relatively low. Removal of bedrock would be difficult.

TABLE 2.5 (Cont.)

General Response Action	Technology Type	Evaluation Result	Comments
Ex-situ treatment	Filtration	Retained	Effective in removing suspended solids from solutions. Could be used to support other response actions.
	Coagulation/ flocculation	Retained	Effective in enhancing filtration and settling processes.
	Settling/centrifugation (clarification)	Retained	Effective in removing suspended solids from solution. Could be used to support other response actions.
	Evaporation	Retained	Effective in removing suspended and dissolved solids from solution. Could be used to support other response actions.
	Reverse osmosis	Retained	Effective in concentrating contaminants in solution. Could be used to support other response actions.
	Coprecipitation	Retained	Effective conventional method for removing uranium from solution.
	Ion exchange	Retained	Effective conventional method for removing uranium and nitrates from solution.
	Liquid-liquid extraction	Retained	Effective conventional method for removing uranium from solution.
	Supported liquid membranes	Rejected	Method under development for removing metals from solution.
	Magnetic separation	Rejected	Method under development for removing metals from solution.
	Ultraviolet oxidation	Retained	Effective conventional method for degrading nitroaromatic compounds from solution.
	Granular activated carbon	Retained	Effective conventional method for removing TCE from vapor and TCE and nitroaromatic compounds from solution.
	Biosorption	Rejected	Method under development for removing metals from solution.
	Biodegradation	Rejected	Method under development for degrading organic compounds in solution.
	Phytoremediation	Retained	Effective emerging technology for degrading/removing TCE, nitroaromatic compounds, nitrates, and uranium.
	Electrodialysis	Rejected	Suitable only for treating soft water and has relatively high costs.
	Enzyme-catalyzed reduction	Rejected	Method under development for removing nitrates from solution.
	Incineration	Retained	Effective conventional method for degrading organic compounds and reducing waste volumes. Could be used to support other response actions.
Disposal	Off-site facility	Retained	Required for disposition of contaminated solid waste from other remedial options.

3 DEVELOPMENT AND SCREENING OF PRELIMINARY ALTERNATIVES

3.1 INTRODUCTION

The purpose of a FS and the overall remedy selection process is to identify, evaluate, and select appropriate remedial actions that eliminate, reduce, or control risks to human health and the environment. On the basis of the screening and evaluation procedures described in Chapter 2, eight preliminary alternatives were developed for the GWOUs from combinations of appropriate technologies and associated process options. The development of these preliminary alternatives is discussed in Sections 3.2 and 3.3, and the screening process to determine the final alternatives is described in Sections 3.4 and 3.5. The final alternatives retained for subsequent analysis in this FS are identified in Section 3.6.

The alternatives discussed in this chapter were considered in the context of follow-on activities after source removal and control response actions have been implemented at the WSCP and the WSOW. These activities are stipulated in the Records of Decision (RODs) addressing soil and structural contamination at the WSCP and soil and pipeline contamination at the WSOW.

Remedial action for OU1 at the WSOW would include excavation of soil containing TNT, DNT, lead, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). This soil is located primarily along the TNT production lines, two wastewater lagoons, and seven burning grounds. In addition to the contaminated soil, approximately 85,000 linear feet of wooden pipeline that transported TNT wastewater would be removed. Most of the excavated material contaminated with TNT is expected to undergo treatment by incineration; however, any material containing more than 500 ppm lead would be sent for disposal in the engineered disposal facility at the WSCP when it becomes available. The lead-contaminated material that did not meet the waste acceptance criteria for on-site disposal would be treated by chemical fixation (stabilization/solidification) prior to disposal.

Remedial activities associated with the chemical plant ROD (DOE 1993) address source control at the WSCP and include remediation of soil and subsurface materials surrounding building foundations contaminated with uranium and elevated concentrations of certain metals and organic compounds; removal of the foundations of contaminated structures; construction of berms around the raffinate pits to eliminate surface runoff; and dewatering of the raffinate pits. Drums and rubble

disposed of in the raffinate pits during earlier decontamination activities at the WSCP will be removed. These source-control activities would be expected to remove or reduce further migration of contaminants from source materials to the groundwater.

3.2 CRITERIA FOR DEVELOPING ALTERNATIVES

The criteria for developing alternatives are provided in EPA guidance (EPA 1988a) and in the NCP (EPA 1990a). These criteria are used to develop alternatives that protect human health and the environment by controlling risks posed through each exposure pathway at a site. The numbers and types of alternatives to be analyzed are site specific and take into account the scope, characteristics, and complexity of the problem that is being addressed. The following types of alternatives were developed for the GWOUs in accordance with EPA guidance:

- Alternatives that involve treatment as a principal component to reduce the toxicity, mobility, or volume of the COCs in groundwater. As appropriate, this range of treatment alternatives includes an alternative that removes or destroys the COCs to the maximum extent feasible, thereby eliminating or minimizing, to the degree possible, the need for long-term management.
- Containment alternatives that involve little or no treatment but provide protection to human health and the environment by preventing or controlling exposure to the COCs. These alternatives might include engineering controls and, as necessary, institutional controls to protect human health and the environment and to ensure continued effectiveness of the response action.
- A no action alternative — that is, no further action after source removal activities have been implemented and completed at the WSCP and the WSOW — is included as a baseline for comparison with other alternatives. Actions taken to reduce the potential for exposure (e.g., institutional controls such as deed restrictions) are not included as a component in the no action alternative.

The general response actions for groundwater identified in Chapter 2 are (1) no action, (2) institutional controls, (3) monitoring, (4) containment, and (5) extraction and treatment. Institutional controls would include access and legal restrictions. Groundwater monitoring would

include the existing monitoring well network as well as any additional wells to be constructed as part of an alternative action. Containment actions would include interception of groundwater, horizontal and vertical barriers, and containment by pumping. Treatment actions would typically include physicochemical treatment, biological treatment, thermal treatment, and electrical treatment (e.g., electrokinetic remediation).

3.3 IDENTIFICATION OF PRELIMINARY ALTERNATIVES

Preliminary alternatives were assembled from combinations of technologies and associated management strategies (e.g., institutional controls and well restrictions) that were retained following the screening and evaluation process described in Chapter 2. Potential action alternatives were screened to eliminate those alternatives determined too difficult to implement on the basis of unproven technologies, those determined not sufficient to remediate groundwater at the WSCP and the WSOW within a reasonable time period, or those determined to have limited application for the specific contaminant or site conditions (EPA 1988a). The technologies and management strategies that were not eliminated were incorporated into the following preliminary alternatives:

- Alternative 1: No Action;
- Alternative 2: Monitoring with No Active Remediation;
- Alternative 3: Natural Attenuation;
- Alternative 4: Groundwater Removal, On-Site Treatment of TCE and Nitro-aromatic Compounds Using Granular Activated Carbon, and Physical/ Chemical Treatment of Other Contaminants;
- Alternative 5: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using Ultraviolet Oxidation, and Physical/ Chemical Treatment of Other Contaminants;
- Alternative 6: Groundwater Removal, On-Site Treatment Using Phyto-remediation;
- Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater; and
- Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping.

These eight alternatives address the five general response actions for groundwater listed in Section 3.2. The alternatives range from no action, where no further action would be taken at the site, to in-situ and ex-situ treatment of the groundwater, which would prevent or reduce future migration of the contamination toward any off-site receptors.

3.3.1 Factors Common to All Preliminary Action Alternatives

The approaches for implementing these eight preliminary action alternatives contain a number of similar activities. For example, it was assumed that groundwater monitoring would occur under each action alternative for the cleanup period. Monitoring would be needed to evaluate whether the groundwater action was achieving, or would achieve, the intended response objectives. Monitoring would be continued, as needed, for those alternatives not involving active removal of contaminants from the groundwater. In addition, each alternative (other than no action) might require various support operations prior to implementation. These activities could include procurement of appropriate equipment and development of contingency plans and operational controls to minimize contaminant releases. Some action alternatives may involve destruction or storage of removed contaminants in an appropriately permitted facility.

In the analyses performed for this FS, it was assumed that remedial action activities addressing source removal and controls stipulated in RODs for preceding operable units for the WSCP and the WSOW have been implemented.

3.3.2 Factors Specific to Each Preliminary Alternative

3.3.2.1 Alternative 1: No Action

The no action alternative (Alternative 1) is intended to provide a baseline for comparison with the other alternatives evaluated. Under this alternative, no further action would be taken to remediate groundwater at the WSCP and the WSOW, and any currently ongoing maintenance or monitoring would be discontinued. Alternative 1 would not provide for any active or passive institutional controls (e.g., physical barriers or deed restrictions) to reduce the potential for exposure to contaminants currently in the groundwater . By definition, this alternative is a zero-cost alternative that provides no added protection to any receptor in the form of engineering or institutional controls.

3.3.2.2 Alternative 2: Monitoring with No Active Remediation

Alternative 2 would not involve groundwater extraction, in-situ or ex-situ treatment, or containment actions. It would rely upon the groundwater's natural ability to lower contaminant concentrations through physical, chemical, and biological processes until cleanup levels were met (the primary groundwater contaminants are TCE, nitrate, nitroaromatic compounds, and uranium). These processes include adsorption to soil particles (for uranium), biodegradation (for nitroaromatic compounds and TCE), and dilution and dispersion in groundwater. The approach used for this alterative may be considered at sites where groundwater removal has been determined to be technically impracticable and where it has been determined that active remedial measures would not significantly speed remediation time frames. Such a case might require a technical impracticability waiver from meeting the cleanup criteria defined by ARARs.

To ascertain whether cleanup to ARARs is realistic, the Committee on Ground Water Cleanup Alternatives of the National Academy of Sciences (National Research Council 1994) has identified three major classes of sites based on hydrogeology and contaminant chemistry:

- **Class A Sites** — Sites where full cleanup to health-based standards should be feasible using current technology. Such sites include homogeneous (e.g., permeable, well-sorted sands or gravels) single- and multiple-layer aquifers involving mobile, dissolved contaminants.
- **Class B Sites** — Sites where the technical infeasibility of complete cleanup is likely to be uncertain. This class includes a wide range of hydrogeologic settings and contaminant types that do not fall into Classes A or C.
- **Class C Sites** — Sites where full cleanup of the source areas to health-based standards is not likely to be technically feasible. Such sites include fractured-rock aquifers contaminated by free-product light nonaqueous phase liquids (LNAPL) or dense nonaqueous phase liquids (DNAPL), such as TCE, and single- or multiple-layered heterogeneous aquifers contaminated by a free-product DNAPL.

Monitoring and characterization data indicate that most of the contamination exists in the weathered portion of the Burlington-Keokuk Limestone shallow aquifer. The shallow bedrock

aquifer system at the GWOU has been described as a fractured, coarsely crystalline, thickly bedded carbonate containing abundant chert nodules. On the basis of the criteria given by the National Research Council (1994), the technical feasibility of complete removal of nitroaromatic compounds and uranium in the shallow aquifer at the WSCP and the WSOW is likely to be uncertain because of the presence of fractures, which makes it difficult to delineate contaminant pathways, and the high sorption of uranium on subsurface media (K_d = 330; DOE and DA 1998b). For these contaminants, the shallow bedrock aquifer system at the WSCP and the WSOW can be considered to be a Class B site.

The ability to restore groundwater to cleanup levels defined by ARARs might be inhibited if the following factors exist at a site (Goffredi 1997a): large volume, long duration release; low biotic/abiotic decay potential; contaminants low in volatility; large volume of contaminated media; contaminants located at great depth; complex geology (e.g., interbedded and discontinuous in nature); heterogeneous underlying stratigraphy (e.g., interbedded sand and silts, fractured media, karst); low hydraulic conductivity of the contaminated aquifer (i.e., less than 1×10^{-4} cm/s [0.3 ft/d]); and high temporal variation in the groundwater flow regime. Generally, sites that satisfy several of these factors have been stated to be good candidates for a technical impracticability waiver (Goffredi 1997a). These factors may be compared with the prevailing conditions at the WSCP and the WSOW, as follows:

- ***Large Volume, Long Duration Release***: The area over which groundwater contamination is estimated to exist is about 1,600 ha (3,900 acres) for the WSOW (DA 1993). At the WSOW, assuming an average aquifer thickness of approximately 10 m (30 ft), the volume of aquifer that might be potentially contaminated is about 140 million m^3 (5 billion ft^3). At the WSCP, assuming an average aquifer thickness of about 10 m (30 ft) and an areal extent of groundwater contamination of about 40 ha (100 acres), the volume of aquifer that might be potentially contaminated is about 4 million m^3 (130 million ft^3).

  Although all contaminants are not found throughout the affected aquifer, the above calculations are based on the assumption that all groundwater with concentrations above the appropriate risk-based level would be remediated. This FS also examines the possibility of remediating a more limited set of

contaminants, such as TCE. In this case, while the extent of TCE contamination is considerable, it is more limited than the area of nitrate contamination on the WSCP, and the areal extent of groundwater contamination at the WSCP would be more on the order of tens of acres.

In terms of duration, contamination has been seeping into the groundwater since 1941 at the WSOW and the WSCP from wastes resulting from munitions manufacturing, and since 1955 at the WSCP from wastes generated from uranium processing.

- ***Low Biotic/Abiotic Decay Potential***: Any natural biological degradation of TCE at the WSCP would be expected to occur at a slow rate (see Section 2.2.2). Relatively fast degradation rates have been measured in the laboratory for 2,4-DNT and 2,6-DNT. Assuming first-order decay, regression of experimental data for the microbial degradation of 2,4-DNT and 2,6-DNT with time (Bradley et al. 1997) indicates a half-life of 11 to 18 days for 2,4-DNT and 41 to 78 days for 2,6-DNT, on the basis of a 95% confidence level. Nearly complete removal of TNT by microbial degradation has also been achieved in the laboratory in several months (Bradley and Chapelle 1995). However, although these laboratory results indicate the potential for TNT, 2,4-DNT and 2,6-DNT biodegradation, it is expected that the DNT and TNT degradation rates in the field would be significantly slower than in the laboratory because field conditions, such as periodic drying of subsurface media (Bradley and Chapelle 1995), are less optimal.

  Although toxic shock occurs at high nitroaromatic concentrations and blocks their biotic degradation (which would relegate any biological activity to fringe areas where concentrations are lower), groundwater concentrations of nitroaromatic compounds at the WSCP and the WSOW are not high enough to cause toxic shock to any indigenous microbe populations.

  Conditions conducive to microbial degradation of nitrates are found in fine-textured, water-logged soils with high organic content; such conditions do not

exist in the shallow bedrock aquifer system at the WSCP and the WSOW. Water has a direct effect on denitrification: the closer the subsurface medium is to water saturation, the more denitrification may potentially occur. High organic content is conducive to denitrification because microbial denitrifiers need oxidizable organic material as a source of carbon for growth and a source of electrons for the reduction of nitrogenous compounds. It might be expected that any natural biological degradation of nitrates in the shallow aquifer system at the WSCP and the WSOW would occur at a slow rate.

- ***Contaminants Low in Volatility***: The vapor pressure of the following contaminants of concern at both the WSCP and the WSOW — which include nitroaromatic compounds (2,4-DNT: 5.1×10^{-3} mm mercury; 2,6-DNT: 1.8×10^{-2} mm mercury), nitrates (effectively zero), and uranium (effectively zero because it is a nonvolatile solid) — are all very low. Thus, these contaminants are considered to have low volatility.

  TCE, however, has a relatively high vapor pressure of approximately 58 mm mercury and can be considered to have a relatively high volatility.

- ***Large Volume of Contaminated Media:*** The volume of aquifer that might be potentially contaminated is very large, approximately 140 million m^3 (5 billion ft^3) at the WSOW and approximately 4 million m^3 (130 million ft^3) at the WSCP.

- ***Contaminants Located at Great Depth:*** The contaminants are primarily located within the Burlington-Keokuk Limestone shallow bedrock aquifer located at the WSCP and the WSOW; this aquifer is composed of the Burlington-Keokuk Limestone, the Fern Glen Formation, and associated saturated overburden materials. The subsurface within the WSCP and the WSOW consists of unconsolidated deposits that overlie the shallow bedrock aquifer. The thickness of the overburden deposits generally ranges from 5 to 18 m (15 to 60 ft) at the WSCP and from 3 to 17 m (10 to 55 ft) at the WSOW. The thickness of the Burlington-Keokuk Limestone Formation itself

ranges from 0 to less than 46 m (150 ft) beneath and in the vicinity of the ordnance works and from 12 to 56 m (40 to 185 ft) at the WSCP. The groundwater monitoring wells in which contaminants have been detected at levels exceeding the PRGs are generally screened in the Burlington-Keokuk formation at a depth at least 15 m (50 ft) below the surface. The range in depth would make it more difficult to conventionally extract contaminants using vertical wells.

- ***Complex Geology:*** The shallow bedrock aquifer at the WSCP and the WSOW is divided into two units, weathered and unweathered limestone. The weathered limestone contains as much as 60% chert as nodules, breccia fragments, and interbeds. The shallow aquifer is discontinuous within the WSOW because the unweathered unit is not present at certain locations.
- ***Heterogeneous Underlying Stratigraphy:*** The shallow bedrock aquifer at the WSCP and the WSOW is composed of limestone, which is coarsely crystalline, thick bedded, and cherty in nature. Both limestone (uniform porous media) and karst (large isolated fractures) are present. It is conceptualized to be a diffuse flow system where the bedrock is thinly bedded or fractured sufficiently to serve as a uniform porous medium; superimposed conduit flow occurs in large isolated fractures. Water movement in the shallow aquifer has been affected by karst development from solution activity in the carbonate bedrock.
- ***Low Hydraulic Conductivity of the Contaminated Aquifer ($< 1 \times 10^{-4}$ cm/s):*** The hydraulic conductivity of the shallow bedrock aquifer at the WSCP and the WSOW is generally lower than 1×10^{-4} cm/s (0.3 ft/d). Pump tests conducted in wells at three different areas of the WSCP indicated hydraulic conductivities ranging from 5.3×10^{-6} to 8.9×10^{-5} cm/s (0.015 to 0.25 ft/d), below the metric of 1×10^{-4} cm/s (0.3 ft/d). Slug tests performed on 40 wells at the WSOW indicated hydraulic conductivities ranging from 2.1×10^{-8} to 2.8×10^{-5} cm/s (6.0×10^{-5} to 7.9×10^{-2} ft/d).

- ***High Temporal Variation in the Groundwater Flow Regime:*** Two regimes of groundwater flow are postulated to exist in the shallow bedrock aquifer at the WSCP and the WSCP: diffuse flow and turbulent flow. Diffuse flow follows Darcy's law for a porous medium, but the high-velocity turbulent flow that occurs in conduits and in large, isolated fractures does not. Thus, the travel time from the shallow bedrock aquifer to an associated discharge spring can be on the order of only five to eight hours.

  Groundwater flow velocities appear to vary greatly within the shallow aquifer, depending on the location, flow regime, and time of year. Annual cyclic variations on the order of 1.2 to 3 m (4 to 10 ft) have been observed in water level fluctuations; water levels have increased as much as 0.3 m (1 ft) during precipitation. Daily fluctuations in water levels observed at the WSCP and the WSOW during dry weather were as much as 0.3 m (1 ft).

This comparison indicates that any alternative involving extraction and ex-situ treatment would probably not be successful because of the nature of the contamination (large volume, long release duration) and the adverse characteristics of the shallow aquifer, including low conductivity, potentially low sustained pumping yields (about 1.2 L/min [0.3 gpm] [MK-Ferguson and Jacobs Engineering Group 1990a]), and superimposed fractures and weathering. Thus, the WSCP and the WSOW may be good candidates for a technical impracticability waiver. (The factors listed above are examples of generalized site characteristics that may limit the effectiveness of subsurface remediation. It is recognized that the particular factor or combination of factors that may critically limit the restoration potential will be site specific.)

The activities associated with Alternative 2 would include the following:

- Source-control response actions implemented per RODs for the WSCP and the WSOW that would prevent further release of contaminants to groundwater;
- Performance monitoring of groundwater to verify that future contaminant concentrations would not result in unacceptable risks to human health;

- Institutional controls to ensure that contaminated groundwater was not used before protective concentrations were attained; and
- Contingency measures in the event that natural processes did not result in acceptable off-site concentrations and exposure.

Source-control measures for the WSCP and the WSOW are listed in Section 3.1. These actions would prevent or minimize further migration of contaminants from source materials to groundwater. It would, therefore, be expected that the concentrations of contaminants in the WSCP and the WSOW would continue to decrease with time because of removal of the original source of contamination; dilution through infiltration from rainwater and runoff; and natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials.

Several natural underground conduits exist across the WSCP and the WSOW where the groundwater travel time to surface springs is on the order of hours. However, monitoring of the water from these springs has indicated low contaminant concentrations that do not result in unacceptable human health exposures at these groundwater discharge points. Natural processes occurring in groundwater, combined with dilution or dispersion, would likely contribute to contaminant concentrations below PRGs at these springs. Although the exact mechanisms that are naturally occurring cannot be identified, these observations suggest that active remediation of groundwater might not be necessary.

Another activity associated with Alternative 2 would involve continued monitoring of groundwater. Groundwater would be routinely sampled and analyzed to track contaminant migration and degradation (e.g., TCE and nitroaromatic compounds) to verify that the assumptions of the exposure assessment and risk assessment were being met and that potential drinking water supplies would remain protected. The direction and rate of movement of the contaminated groundwater would be tracked as a function of time. Groundwater monitoring under Alternative 2 would continue for a reasonable period of time (i.e., greater than 10 years) or until remedial objectives were met.

Groundwater would be monitored using the existing well network, as appropriate. Additional monitoring wells might be installed and sampled to evaluate the protectiveness of this alternative. For conservatism, Alternative 2 was assumed to involve the construction and operation of 15 additional monitoring wells, which is approximately 10% of the number of existing wells. The

exact monitoring network and details regarding frequency of sampling and parameters analyzed would be identified in the ROD or subsequent remedial design/remedial action reports, as appropriate. In general, monitoring of the additional wells would take into account the migration patterns and any seasonal influences.

Institutional controls that might be applied for the WSCP and the WSOW groundwater include land use restrictions and continued federal ownership. Land use restrictions could include St. Charles County zoning regulations and deed restrictions by the Missouri Department of Conservation on land not currently under federal ownership (e.g., August A. Busch Memorial Conservation Area). Zoning of properties other than the WSCP and the WSTA at the WSOW might become relevant under some future period. Deed restrictions would involve specific limitations on future land use that are incorporated in the deed of ownership to the property. Such restrictions would prevent activities that could cause direct exposure or releases of groundwater contaminants. Deed restrictions accompany the deed to the property in a manner that is generally binding and must be transferred to all subsequent owners of the property. Examples of deed restrictions include those prohibiting residential or agricultural use. Drilling for mineral, water, or other purposes would also be prohibited.

Continued federal ownership of the WSTA by the DA and of the area containing the on-site disposal cell at the WSCP by the DOE is certain. This will result in continued control of these areas by the federal government, with the intent to restrict site development activities through the rights of ownership. On-property development activities, such as agricultural or residential use, could be restricted or eliminated by the federal government which, as the property owner, would retain all rights to preclude these activities.

Because contaminants would remain on-site above levels that allow for unlimited use and unrestricted exposure under Alternative 2, reviews would be conducted at least every five years after the remedy was completed to ensure that it continued to provide adequate protection of human health and the environment. However, to further optimize interpretation of future monitoring results, it may be worthwhile to obtain data from the network of wells after source removals have been completed and a significant amount of time has elapsed to allow for beneficial impacts from source removals to occur (e.g., after three years or more). The sampling frequency would depend on the location of the monitoring wells and the groundwater flow velocity. The number of monitoring wells and

sampling frequency would be determined in collaboration with the regulators. (Response measures might be considered if data indicated that future migration of contamination would result in unacceptable off-site exposure. Contingency measures to prevent exposure to contaminated groundwater could include developing an alternative water supply for the public [which could be provided by a wide range of actions, such as well relocation, selective use of wells, or connection to an existing system or surface water source], well head treatment, and use restrictions.)

3.3.2.3 Alternative 3: Natural Attenuation

Natural attenuation is defined in the NCP as "biodegradation, dispersion, dilution, and adsorption" of contaminants in groundwater. The NCP preamble states that natural attenuation is generally recommended when active restoration is not practicable, cost effective, or warranted on the basis of site-specific conditions (e.g., where groundwater is not a likely source of drinking water) or when natural attenuation could achieve remedial goals in a reasonable time frame. Natural attenuation may be a useful remedial approach if site-specific data indicate that these processes would effectively reduce contaminants in the groundwater to concentrations protective of human health and the environment in a time frame comparable to that which could be achieved through active remediation (EPA 1988b).

Natural attenuation relies on natural subsurface processes to reduce contaminant concentrations to acceptable levels. Such processes include dilution, volatilization, biodegradation, adsorption, chemical reactions with subsurface materials, and radioactive decay. Further information on natural attenuation is provided in Section 2.2.2. Natural attenuation has been stated to have many advantages over conventional engineering remediation alternatives (Goffredi 1997b), including the following:

- Contaminants are ultimately transformed into innocuous by-products (such as CO_2, ethylene, ethane, Cl^-, and water for TCE) and not just transferred to another phase or location in the environment;
- Attenuation allows use of the existing infrastructure at a site during remediation;

- Contaminants are generally not transferred to the atmosphere, which prevents increased risk to nearby populations and the environment.
- Attenuation is less expensive than currently available remediation technologies such as conventional extraction and ex-situ treatment ("pump and treat");
- No equipment downtime or maintenance is involved;
- The most mobile and toxic organic compounds are usually the most susceptible to biodegradation.

Hydrogeologic constraints can limit the effectiveness of active restoration when plumes migrate into formations from which they cannot easily be removed; in these special situations, natural attenuation with monitoring and institutional controls has been identified as potentially being the only feasible remedy (EPA 1988b). Such situations include sites with contaminant migration into formations with a high degree of secondary permeability, such as fractured bedrock or karst aquifers. For comparative purposes, the shallow bedrock aquifer system, which contains the majority of the groundwater contamination, has been conceptualized to be a diffuse flow system where the bedrock is thinly bedded or fractured sufficiently to serve as a uniform porous medium; superimposed conduit flow occurs in large isolated fractures. These conditions indicate that a karst hydrologic system is in operation in the bedrock beneath and around the site; this suggests that it may not be practicable or feasible to fully restore groundwater by active remediation.

The conditions potentially favoring the use of natural attenuation are as follows (EPA 1988a): groundwater naturally unsuitable for consumption, low-mobility contaminants, low concentrations of contaminants, low potential for exposure, and low projected demand for future use of the groundwater. These conditions may be compared with the prevailing conditions at the WSCP and the WSOW, as follows:

- ***Groundwater Naturally Unsuitable for Consumption*:** Groundwater that is naturally unsuitable for consumption includes groundwater that is saline (total dissolved solids levels over 10,000 mg/L) or groundwater that is not available in sufficient quantity at any depth to meet the needs of an average household. Existing data suggest that long-term sustainable pumping rates are very low,

about 1.2 L/min (0.3 gpm), from wells installed in the shallow bedrock aquifer where the majority of the contamination is located (MK-Ferguson and Jacobs Engineering Group 1990a).

- ***Low-Mobility Contaminants*:** Information on contaminant mobility (see Section 2.2.2) indicates that precipitation of uranium from solution as insoluble UO_2 may be occurring within the shallow aquifer. Nitroaromatic compounds found in the soil overburden exhibit relatively low water solubility and, therefore, low leachability and mobility. Also, none of the nitroaromatic compound contaminants are highly volatile (DA 1993).
- ***Low Concentrations of Contaminants*:** Nitroaromatic contamination within the shallow aquifer system is widespread and occurs at low concentrations throughout the aquifer (DOE and DA 1998b). However, the uranium, TCE, and nitrate contamination is more localized (i.e., in the vicinity of the raffinate pits at the WSCP).
- ***Low Potential for Exposure*:** The likelihood that groundwater from the shallow aquifer system would be used for residential purposes is low. Access to the WSCP and WSTA by the general public is restricted, and groundwater from the shallow aquifer is unlikely to be used by the public in the future (DOE 1995). The DA expects to retain ownership of the WSTA and to continue using this property for training activities. At the WSCP, a disposal cell is being built on-site that will occupy approximately one-third of the total area.
- ***Low Projected Demand for Future Use of the Groundwater*:** Groundwater occurs in three principal bedrock aquifer systems: (1) the shallow aquifer that is contaminated; (2) a middle confined aquifer composed of the Kimmswick Limestone; and (3) a deep confined aquifer. Groundwater that is used as a drinking water supply in the area is primarily taken from the deep productive aquifer of the Ordovician/Cambrian bedrock system and from an alluvial aquifer near the Missouri River. The projected demand of the groundwater

within the shallow aquifer system is expected to be low on the basis of foreseeable land use and on the low pumping yield (about 1.2 L/min [0.3 gpm] for a single well [MK-Ferguson and Jacobs Engineering Group 1990a]) measured in the area of highest conductivity at the WSCP (i.e., the groundwater trough north of the divide and along the western edge of the WSCP).

This comparison indicates that conditions at the WSCP and the WSOW potentially favor the use of natural attenuation.

Guidance on the use of natural attenuation is evolving. A protocol has been developed for determining the feasibility and effectiveness of using natural attenuation in remediating groundwater contaminated with chlorinated aliphatic hydrocarbons (such as TCE) at DA and DOE sites; this protocol is summarized in Wiedemeier et al. (1996). Consideration of natural attenuation as a potential option requires modeling and evaluation of contaminant degradation rates and pathways. The primary objective of such modeling would be to demonstrate that natural processes of contaminant degradation would reduce contaminant concentrations below regulatory standards or cleanup goals before potential exposure pathways would be encountered. This groundwater modeling would require a thorough understanding of how site geology, hydrology, geochemistry, and microbiology can impact the behavior of contaminants. The following data are required (Wiedemeier et al. 1996):

- Extent and type of soil and groundwater contamination;
- Location and extent of contaminant source areas;
- Information on whether the source will continue to release contaminants;
- Aquifer geochemical characteristics;
- Regional hydrogeologic information; and
- Local and site-specific hydrogeologic data, including information on drinking water aquifers, locations of wells and surface water bodies, patterns of aquifer use (current and future), lithology, site stratigraphy, grain-size distribution, aquifer hydraulic conductivity, groundwater hydraulic gradient, porosity,

dispersivity, preferential flow paths, and areas of local groundwater recharge and discharge.

Extensive soil and groundwater contaminant data are available for both the WSCP and the WSOW. However, to document the occurrence of natural attenuation, groundwater data would be needed regarding decay products and geochemical parameters to determine the three-dimensional contaminant distribution.

Additional data would be needed to determine other model input parameters under aquifer conditions (e.g., biodegradation rate constants and sorption coefficients [K_d] for each contaminant). Table 3.1 lists the analytical parameters used to provide information on whether natural attenuation of chlorinated aliphatic hydrocarbons such as TCE is occurring. (Currently, no natural attenuation sampling protocols are available for nitroaromatics, nitrates, and uranium.) Sampling and sample analysis would be conducted throughout the operational duration of Alternative 3 to confirm that natural attenuation was proceeding at rates consistent with meeting cleanup objectives.

Similar to Alternative 2, the activities associated with Alternative 3 would involve continued groundwater monitoring. A more elaborate sampling and analytical scheme would be required to verify that natural attenuation was occurring at rates that would ensure no off-site migration of contaminant concentrations above health-based levels. Groundwater sampling would be conducted within the contaminated zone to document that natural attenuation was occurring. Also, sampling would be performed outside the contaminated area to identify any migration of

TABLE 3.1 Analytical Parameters That Provide Information on Natural Attenuation of Chlorinated Aliphatic Hydrocarbons

Alkalinity	Oxidation-reduction potential
Chloride concentration	Oxygen (dissolved)
Conductivity	pH
Hydrogen (dissolved)	Sulfate concentration
Iron (II)	Temperature
Methane, ethane, and ethylene concentrations	Total organic carbon
Nitrate concentration	Volatile organic compounds

Source: Wiedemeier et al. (1996).

contaminants that might require initiation of more active remedial measures. The direction and rate of movement of the contaminated groundwater would be tracked as a function of time. Under Alternative 3, groundwater monitoring would continue for a reasonable period of time (i.e., greater than 10 years) or until remedial objectives were met.

Groundwater monitoring would be conducted using the existing well network, as appropriate. Additional monitoring wells might be installed and sampled to evaluate the protectiveness of this alternative and to detect the migration of contaminated groundwater. These wells would be placed approximately 150 m (500 ft) downgradient of the leading edge of the contaminated groundwater or at the distance estimated to be traveled by the groundwater in two years, whichever was greater. For conservatism, this alternative would include the construction and operation of 38 additional monitoring wells, which is approximately 25% of the number of existing wells. All wells would be screened in the same hydrogeologic unit as the contaminated groundwater (i.e., Burlington-Keokuk Limestone). The exact monitoring network and details regarding frequency of sampling and parameters analyzed would be identified in the ROD or subsequent remedial design/ remedial action reports.

Because contaminants would remain on-site at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years after the remedy was completed to verify that it continued to provide adequate protection of human health and the environment. If monitoring showed that the contaminated area and level of contaminants in the groundwater had decreased significantly during the five-year period, the number of wells sampled and the sampling frequency might be reduced. Wells that duplicated information (e.g., wells located less than 15 m [50 ft] apart within the same aquifer, screened over the same interval, and exhibiting similar contaminant concentration profiles), provided unreliable information (e.g., wells that were dry part of the year), or sampled groundwater concentrations below the PRGs for all contaminants might be considered for elimination (Air Force Center for Environmental Excellence 1997). The sampling frequency would depend on the location of the monitoring wells and the groundwater flow velocity. The number of monitoring wells and sampling frequency would be determined in collaboration with the regulators.

Active response measures would be considered if data indicated that future migration of contaminants would result in unacceptable exposure concentrations. These contingency measures

could include installation of a conventional pump-and-treat system using a design similar to that proposed for Alternative 4 (Section 3.3.2.4) and Alternative 5 (Section 3.3.2.5) for containment of the contaminated groundwater.

As for Alternative 2, a technical impracticability waiver from meeting the remediation goals might be needed for Alternative 3 unless it could be shown that cleanup levels were expected to be achieved in a reasonable time frame.

3.3.2.4 Alternative 4: Groundwater Removal, On-Site Treatment Using Granular Activated Carbon

Alternative 4 would involve extraction and ex-situ treatment of the WSCP and the WSOW groundwater to achieve PRGs for groundwater. Groundwater concentrations exceeding these limits would be removed using conventional vertical extraction wells, pumped to and treated in an above-ground treatment system consisting of a sequence of physical and chemical unit operations, and released to a permitted discharge point. If discharged to a surface water (e.g., the Missouri River), the treated water might be required to meet federal and state effluent standards. This analysis conservatively assumed that compliance with these standards would be required. Reinjection of the treated groundwater back into the aquifer was not considered desirable because of the large number of required injection wells and the low hydraulic conductivity of the shallow aquifer. An approach identical to Alternative 2 would be used for management of the portions of the shallow aquifer with groundwater concentrations below the PRGs.

Groundwater extraction and treatment (i.e., "pump and treat") is a widely applied remedial technology. Groundwater extraction systems are relatively simple to design, can be readily constructed and operated, and use standard equipment available from many sources. These systems are used to enhance free product recovery, contain a dissolved contaminant plume, and reduce the mass of contamination in an aquifer. Groundwater extraction wells used in aquifer remediation are typically located near the area of highest contaminant concentrations or near the leading edge of the plume. If located near the leading edge of the plume, the groundwater withdrawal typically intercepts the downgradient extent of the contaminant plume. For a well-defined contaminant plume, conventional extraction is often the first line of defense in preventing further migration and in removing the majority of the contamination.

The first step during construction would involve installation of the vertical extraction wells, which is generally conducted by drilling into the aquifer. The selection of a drilling method is a function of site-specific geologic conditions, well specifications, and degree of subsurface disturbance. Three drilling methods (i.e., hollow stem auger, water/mud rotary, and air rotary) are generally considered when installing wells for groundwater extraction. This analysis assumed the use of water/mud rotary drilling because of the size of the extraction well (a 15-cm [6-in.] extraction well was assumed in this design because it contains adequate space for pumps and pipes for most extraction systems). After each well installation, the drilling equipment, riser, and caps, as well as drilling tools, would be decontaminated.

Between approximately 300 and 930 vertical extraction wells at the WSCP and between 27 and 80 wells at the WSOW (Appendix C) were assumed to be required to achieve a reasonable extraction rate and to contain further spread of contaminants. The wells would be between 15 m (50 ft) and 24 m (80 ft) deep, have a screened length of 10 m (30 ft), and be 15 cm (6 in.) in diameter. Additional investigation of aquifer characteristics would be necessary for detailed evaluation of the placement of the extraction wells and estimation of groundwater extraction rates. The actual location, size, capacity, and depth of the various extraction wells would be determined during the remedial design phase, at which time the hydrogeologic characteristics (i.e., permeability, thickness of the aquifer, depth of the affected groundwater) and the delineation of the contaminated area would be taken into account.

The extracted groundwater would be contained in an aboveground tank prior to pumping for treatment. Contaminated groundwater would be pumped through polyvinyl chloride (PVC) pipes directly to the treatment process. A pipeline would be constructed connecting the discharge of the aboveground tank with the appropriate groundwater treatment facility.

Under Alternative 4, two groundwater treatment facilities with similar treatment capabilities were assumed to be constructed, one to treat extracted groundwater from the WSCP and another for the WSOW. (Remediation of groundwater at the WSOW would not need treatment to remove TCE or nitrates, and, as such, the treatment processes associated with these contaminants, e.g., reverse osmosis for nitrate removal, would not be applied for the WSOW.) The general-use treatment facilities would be single-story, metal frame structures that would house the groundwater treatment system, water storage tanks, pumps, and ancillary equipment. These facilities would have treatment

capacities from 760 to 2,400 L/min (200 to 620 gpm) for the groundwater extracted from the WSCP and from 24 to 72 L/min (6 to 19 gpm) for the WSOW groundwater. The facility footprint would range from 360 to 750 m^2 (3,900 to 8,000 ft^2) for the WSCP and from 42 to 70 m^2 (450 to 740 ft^2) for the WSOW, depending on the number of extraction wells required. (This analysis also considered the use of existing on-site wastewater treatment facilities such as the Quarry Water Treatment Plant [QWTP] and the Site Water Treatment Plant [SWTP]. The QWTP was rejected for groundwater treatment at the GWOU because of the presence of TCE and nitrates. The SWTP would be considered in the remedial design for treatment of extracted groundwater, if available and determined to be cost effective.)

A preconceptual process flow diagram for groundwater treatment is provided in Figure 3.1. This process is similar to that currently applied for treatment of contaminated surface water by the SWTP at the WSCP. In the analysis for this FS, it was assumed that if the effluent from groundwater treatment was discharged to a surface water body, the treated water might be required to meet federal and state effluent standards.

The extracted groundwater would first be sent to a feed tank to dampen variations in flow and groundwater quality among the extraction wells, thereby providing equalization of influent. Uranium and other metals would be removed within the mix tank by precipitation. Several precipitation additives are available. Although lime is the most common precipitant in general use because of its low cost, lime tends to be inefficient because of the volume of sludge produced. This analysis assumed the use of lime; an additive (or combination of additives) would be selected during the remedial design/remedial action phase on the basis of cost and volume of sludge produced. Following precipitation, the precipitate would be rapidly transferred to the clarifier where the solids in the precipitate mixture would settle to the bottom. Sludge from the clarifier, containing the solids and precipitated uranium and other metals, would be dewatered using a filter press. The solid sludge would be sent for disposal.

Clarifiers are generally sufficient for the removal of suspended solids. However, because solids from precipitation or filter backwash sometimes coagulate and settle poorly, multimedia filters would be included to remove any fine particles that did not settle out in the clarifier.

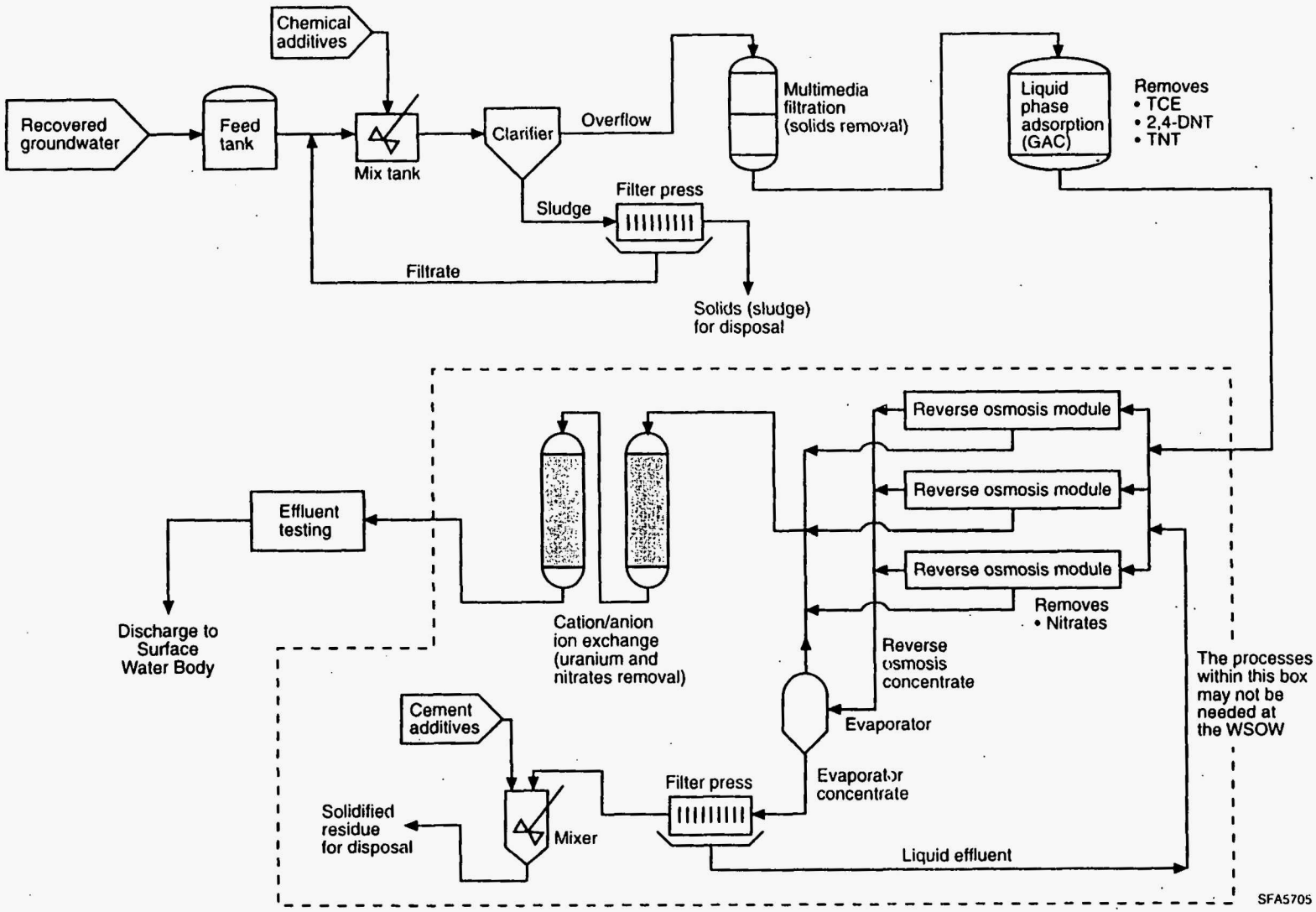

FIGURE 3.1 Process Flow Diagram for Proposed Groundwater Treatment under Alternative 4

GAC would be used to remove organic materials, including nitroaromatic compounds (such as 2,4-DNT and TNT) and TCE by chemically and physically binding them to the carbon. In liquid-phase carbon adsorption, the groundwater would be passed through beds containing activated carbon where the contaminants would be adsorbed.

Ionic species such as nitrates would be removed by reverse osmosis by forcing the contaminated water across a semipermeable membrane, which would result in a reduction in mineral content in the groundwater, thereby removing nitrates. Treatment by reverse osmosis would result in a permeative stream with low concentrations of ions and a low-volume reject stream containing the concentrated dissolved compounds. This reject stream would be sent to an evaporator for further concentration. The evaporator concentrate would be dewatered using a filter press and then mixed with cement additives to produce a solidified residue (grout) for disposal purposes. (Groundwater treatment at the WSOW would not require reverse osmosis for nitrate removal.)

Because this method has been widely applied for the treatment of high flows of wastewater with dilute concentrations of metals, ion exchange would be used to remove trace amounts of uranium from the groundwater. In ion exchange, the contaminants are exchanged with ions of the resin (e.g., sodium [Na^+]). (Groundwater treatment at the WSOW would not require ion exchange for uranium removal.) The treated water from the ion-exchange units would be chemically analyzed to verify that the water had been treated to permissible levels and to confirm compliance with the requirements of a National Pollutant Discharge Elimination System (NPDES) permit. Effluent pH adjustment was not considered necessary in this analysis, but could easily be added to the system if required. When the treated water passed appropriate federal and state effluent standards, it would be discharged.

Liquid-phase carbon adsorption would be used under Alternative 4 for removal of organic compounds from the groundwater. This technology is well developed and widely used, and it is very effective in removing a wide range of organic contaminants from groundwater, including TCE and explosives. It is a transfer technology only, however, and the carbon adsorption media would require replacement after reaching its capacity. In liquid-phase carbon adsorption, the contaminated groundwater would come in contact with the GAC by flowing through a series of packed bed adsorbers (which are simply columns packed with GAC). The activated carbon selectively adsorbs organic compounds that are attracted to and held in the internal micropores of the carbon granules. This

analysis assumed the use of downflow fixed-bed GAC adsorbers (see Figure 3.2), because they constitute a cost-effective treatment technology that produces the lowest effluent concentrations compared with other carbon adsorber designs.

The system described for Alternative 4 should be effective for removing TCE, nitrates, nitroaromatic compounds, and uranium. (The process flow diagram in Figure 3.1 is provided for purposes of illustration and is not intended as a final or definitive treatment system. Other treatment processes or system configurations could be used, provided they were capable of cost effectively achieving the required effluent concentrations.) In general, however, the removal characteristics of any particular combination of contaminants in a waste stream are not predictable. A pilot test using a sample of the groundwater of interest under comparable conditions might be required to accurately determine the optimal process and its characteristics. The actual design for treatment of the extracted groundwater would be determined during the remedial design phase, at which time the necessary flow capacity, required contact time to achieve contaminant concentration reduction, and contaminant concentrations likely to be encountered would be taken into account.

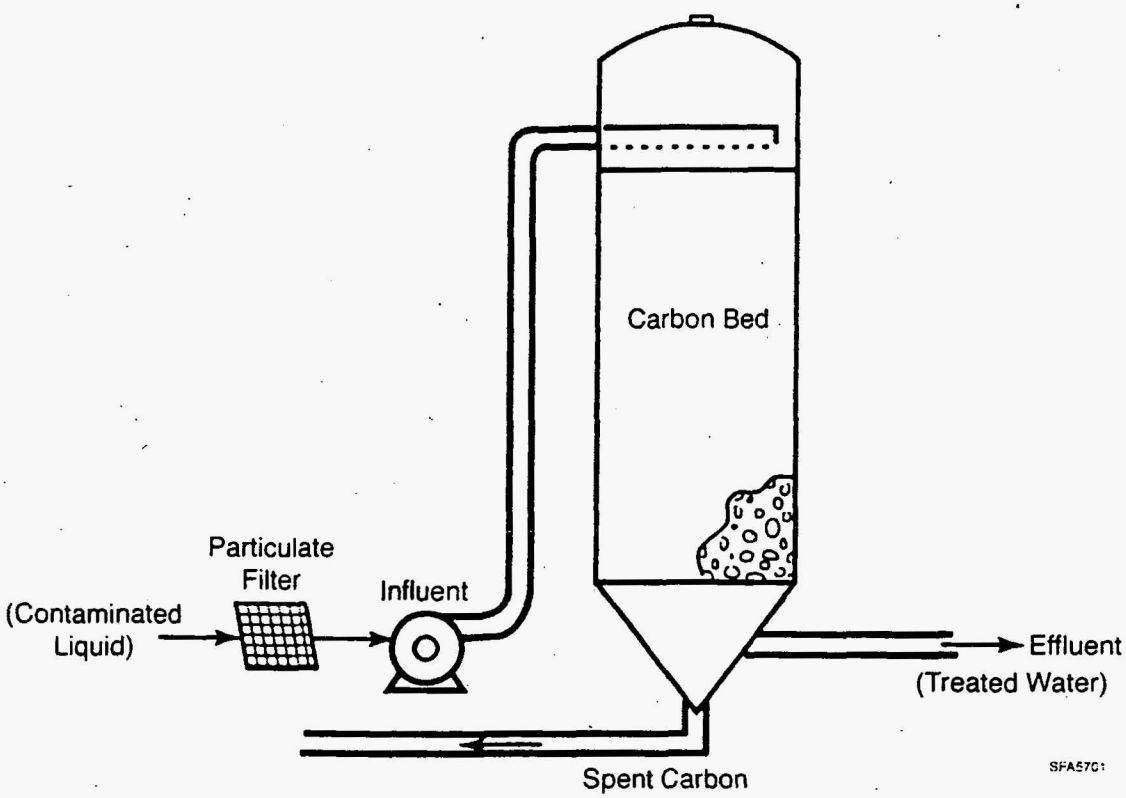

FIGURE 3.2 Typical Fixed-Bed GAC Adsorption System (Source: Marks et al. 1994)

Any sludge generated by groundwater treatment at the WSCP and the WSOW was assumed to be managed similarly to sludge generated by the water treatment process at the SWTP. This sludge is currently placed into 3-m^3 (4-yd^3) boxes and then transported to the temporary storage area at the WSCP. The sludge is placed within a bermed area constructed on top of the fine-grained soil pile at the temporary storage area and allowed to dewater. Eventually, the sludge is mixed within the fine-grained soil matrix (Valett 1997); this mixture is then disposed of in the on-site engineered disposal facility when it becomes available.

Following closure of the on-site disposal facility at the WSCP, the dewatered sludge from the GWOU would be packaged for off-site shipment and disposal. If the waste-acceptance criteria for off-site disposal are met, the dewatered sludge would be shipped via truck to an off-site licensed disposal facility (transport by rail does not appear to be an option because of the lack of a nearby railhead for shipping). Assuming packaging in a standard 55-gal (208-L) drum and truck transport, only one off-site shipment to a licensed disposal facility would be required annually.

If necessary to meet the waste acceptance criteria for off-site disposal, the sludge would be treated by chemical fixation (stabilization/solidification) prior to disposal. Most of the solids in the sludge would be normal (uncontaminated) dissolved solids such as calcium carbonates and hydroxides. Treatability studies prior to the remedial design might be required to determine the most appropriate approach to follow.

The maximum radioactivity of the dewatered sludge is estimated to be about 60 pCi of uranium per gram of sludge for the WSCP groundwater and less than 1 pCi of uranium per gram of sludge for the WSOW groundwater. These values are based on the maximum detected concentrations of 870 and 10 pCi/L measured during monitoring at the WSCP and the WSOW, respectively (DOE and DA 1998b), and an assumed 1.5 g of sludge per 100 g of wastewater [Shropshire et al. 1995]). Both values are much less than the maximum average concentration of 18,000 pCi/g of uranium allowed in waste sent to the Envirocare facility for off-site commercial disposal. These estimates could actually be much lower because more recent maximum concentrations of uranium at the WSCP and the WSOW are lower (i.e., the maximum concentrations reported were 60 pCi/L for wells at the WSCP [MW-4024] and 2 pCi/L for wells at the WSOW). In fact, it is suspected that the 60 pCi/L could have been due to the bentonite grout used for installing well MW-4024 in 1995.

The replacement schedule for spent GAC would depend on the adsorption efficiency under actual operating conditions. For conservatism in this analysis, the spent carbon was assumed to be replaced every three months. The spent carbon would then be regenerated at the supplier facility or sent to a commercial disposal facility. Because off-site thermal regeneration of GAC contaminated with explosives is currently under development (PNNL 1997), this analysis assumed disposal of the spent contaminated carbon. For a carbon fill of 400 kg (880 lb), the amount of spent carbon to be disposed of annually as hazardous waste would be approximately 1,600 kg (3,500 lb). Assuming packaging in standard 55-gal (208-L) drums and truck transport, less than one annual off-site shipment to a licensed disposal facility would be required for both the WSCP and the WSOW groundwater treatment facilities. On the basis of literature values of carbon adsorption capacity for various compounds (EPA 1995b), the spent carbon would contain approximately 2 wt% contaminant (primarily TCE for the WSCP and nitroaromatic compounds for the WSOW).

The air would be monitored to detect airborne contamination generated during remedial activities, so that appropriate mitigative measures could be taken. Long-term air monitoring would be implemented following completion of construction to ensure detection of any potential airborne releases of contaminants associated with duct leaks or maintenance of the GAC treatment system. The sites would continue to perform environmental monitoring to the extent necessary to ensure long-term performance of the remedy.

3.3.2.5 Alternative 5: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using Ultraviolet Oxidation

The objectives and design of Alternative 5 are similar to those for Alternative 4, except that on-site treatment using UV oxidation was assumed for Alternative 5. UV oxidation technology would replace the GAC process applied in Alternative 4 for the removal of TCE and nitroaromatic compounds from the extracted groundwater. Groundwater contaminants exceeding the PRGs would be removed by using conventional vertical extraction wells. Contaminated groundwater would be pumped to and treated at an aboveground treatment system, consisting of a sequence of physical and chemical unit operations, and would then be released to a permitted discharge point. An approach identical to Alternative 2 would be used for managing the portions of the shallow aquifer with groundwater concentrations below the PRGs.

UV oxidation is a relatively new treatment technology that has been used as a full-scale application to treat groundwater for more than 12 years. It has not been used extensively for remediating water contaminated with organic compounds because of the widespread use of GAC treatment. UV oxidation can be an effective treatment for water contaminated with TCE and explosives, and, unlike carbon adsorption, actually destroys these compounds rather than just transferring them to a more easily disposable medium. UV oxidation uses UV light in conjunction with an oxidant or cavitation to produce free radicals. These free radicals oxidize the contaminant to produce a simpler molecule that is nonhazardous. In this case, the UV light energy (photon) is absorbed by the oxidant, either H_2O_2 or ozone (O_3), to form a hydroxyl radical (OH•). Some systems use a combination of these two oxidants to improve the stoichiometry of the chemical reaction. This analysis assumed that the oxidizer (H_2O_2) would be added through a traditional feed system consisting of a tank with secondary containment, one to two feed pumps, and distribution piping (see Figure 3.3).

The UV oxidation system causes the TCE to react to form nontoxic by-products that can be released directly to the environment. The UV oxidation process can treat cyanides, carbonyls, many aromatic compounds, phosphorus and sulfur pesticides, PCBs, and dioxins. UV oxidation is not applicable to heavy metals, fluorides, acids, and many aliphatic compounds.

A preconceptual process flow diagram for groundwater treatment including UV oxidation is provided in Figure 3.4. This system would be expected to remove uranium, nitrates, and other

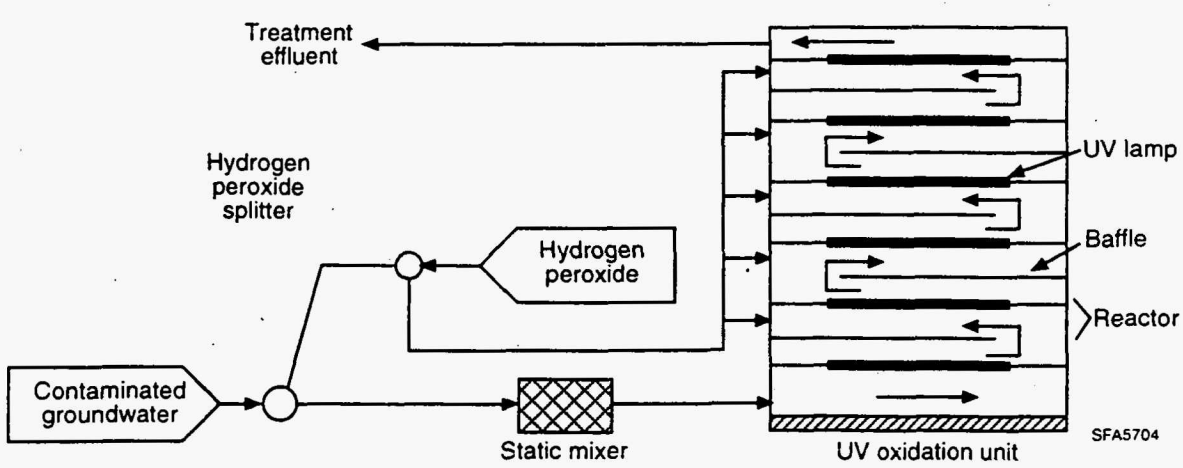

FIGURE 3.3 Ultraviolet Oxidation Treatment System (Source: Adapted from EPA 1995b)

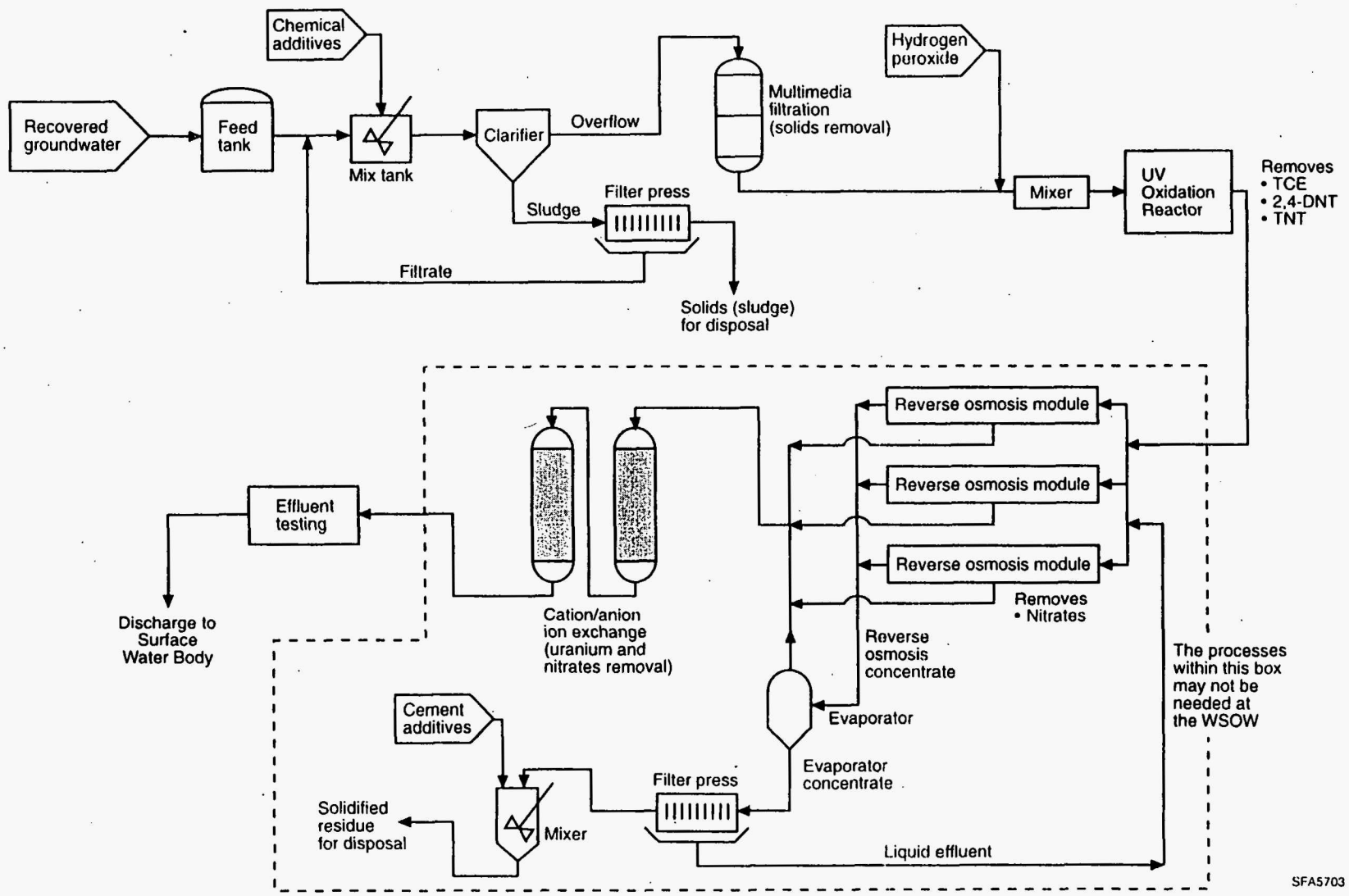

FIGURE 3.4 Process Flow Diagram for Proposed Groundwater Treatment under Alternative 5

compounds to conform with effluent limits associated with surface water discharge limits. The system is described primarily for purposes of illustration and is not intended as a final or definitive treatment system. Other treatment processes or system configurations could be used, provided they were capable of cost effectively achieving the required effluent concentrations. The system described here shows a representative process option that was assumed to be effective for removal of TCE, nitrates, nitroaromatic compounds, and other contaminants detected in the groundwater at the WSCP and the WSOW. (Removal of uranium and nitrates would not be required for groundwater from the WSOW.)

The characteristics of Alternative 5 would be very similar to those of Alternative 4, except that no spent carbon would be generated. The sites would continue to perform environmental monitoring to the extent necessary to ensure long-term performance of the remedy.

3.3.2.6 Alternative 6: Groundwater Removal, On-Site Treatment Using Phytoremediation

The objectives and design of Alternative 6 are similar to Alternative 4, except that on-site treatment using phytoremediation was assumed for Alternative 6. Groundwater contaminants exceeding the PRGs would be removed by using conventional vertical extraction wells. Contaminated groundwater would be pumped to and treated at aboveground constructed wetlands and released to a permitted discharge point.

Phytoremediation is the use of enzymatic activity occurring in plants at the root level to remediate contaminated groundwater. Phytoremediation has been reported to be most suited for sites containing groundwater with moderately hydrophobic contaminants, which include chlorinated solvents such as TCE, nitrotoluene ammunition wastes such as TNT and DNT, excess nutrients such as nitrate, and heavy metals. Plant species can extract and assimilate or extract and chemically decompose target organic contaminants. Heavy metals can be taken up and bioaccumulated in plant tissues. Inorganic compounds such as nitrates, which are considered to be environmental contaminants in groundwater, are in fact vital plant nutrients that can be absorbed through the root system for use in growth and development. In general, plants will survive higher concentrations of hazardous wastes than will most microorganisms used for bioremediation.

Phytoremediation has been effective in a number of full-scale and pilot-scale studies. It has already been successfully implemented by the DA to clean TNT and hexahydro-1,3,5-trinitro-1,3.5-triazine (RDX) from contaminated wetlands (Boyajian and Carreira 1997). Levels of TNT were reduced by more than 99% using a variety of native aquatic and wetland plants (Boyajian and Devedjian 1997). Studies performed by the EPA involving phytoremediation using the parrot feather plant indicated that dissolved TNT concentrations decreased from 128 ppm (saturation conditions) to 10 ppm in one week (Schnoor et al. 1995).

Constructed wetlands have been proven to be effective for treating municipal wastewater and acid mine drainage by using natural geochemical and biological processes inherent in an artificial wetland ecosystem to accumulate and remove nitroaromatic compounds and other contaminants from influent waters. Certain plants native to wetland environments support nitroreductase and lactase enzymes that can degrade complex nitrogen-based compounds into benign substances. The parrot feather and Eurasian water milfoil plants have been applied in aquatic mesocosms to break down nitroaromatic compounds. Enzymes have been shown to break down nitroaromatic compounds and incorporate the broken ring structures into new plant material or organic detritus that becomes part of sediment organic matter (Schnoor et al. 1995). Another plant-derived enzyme, dehalogenase, helps reduce chlorinated solvents such as TCE to chloride ion, carbon dioxide, and water.

Under Alternative 6, two constructed wetlands would be built, one to treat extracted groundwater from the WSCP and another for the WSOW. A constructed wetland consists of a lined, man-made lagoon with a variety of plants, including parrot feather, which is located outdoors (see Figure 3.5). Two basic types of constructed wetlands are used in the United States: free-water surface flow and subsurface flow (Reed and Brown 1992). The major difference is that the water level is designed to remain below the surface of the media for the subsurface flow wetland, whereas the water surface is exposed to the atmosphere for the free-water surface flow wetland. For this analysis, the free-water surface flow wetland design was assumed to be applied at the Weldon Spring area to allow photolysis of the nitroaromatic compounds and evaporation of the TCE.

In a free-water surface-flow wetland, groundwater is typically introduced across one end of the constructed wetland by either a concrete channel with V-notch weirs or by a perforated pipe located within the crushed rock inlet zone. The distribution channel and inlet zone uniformly

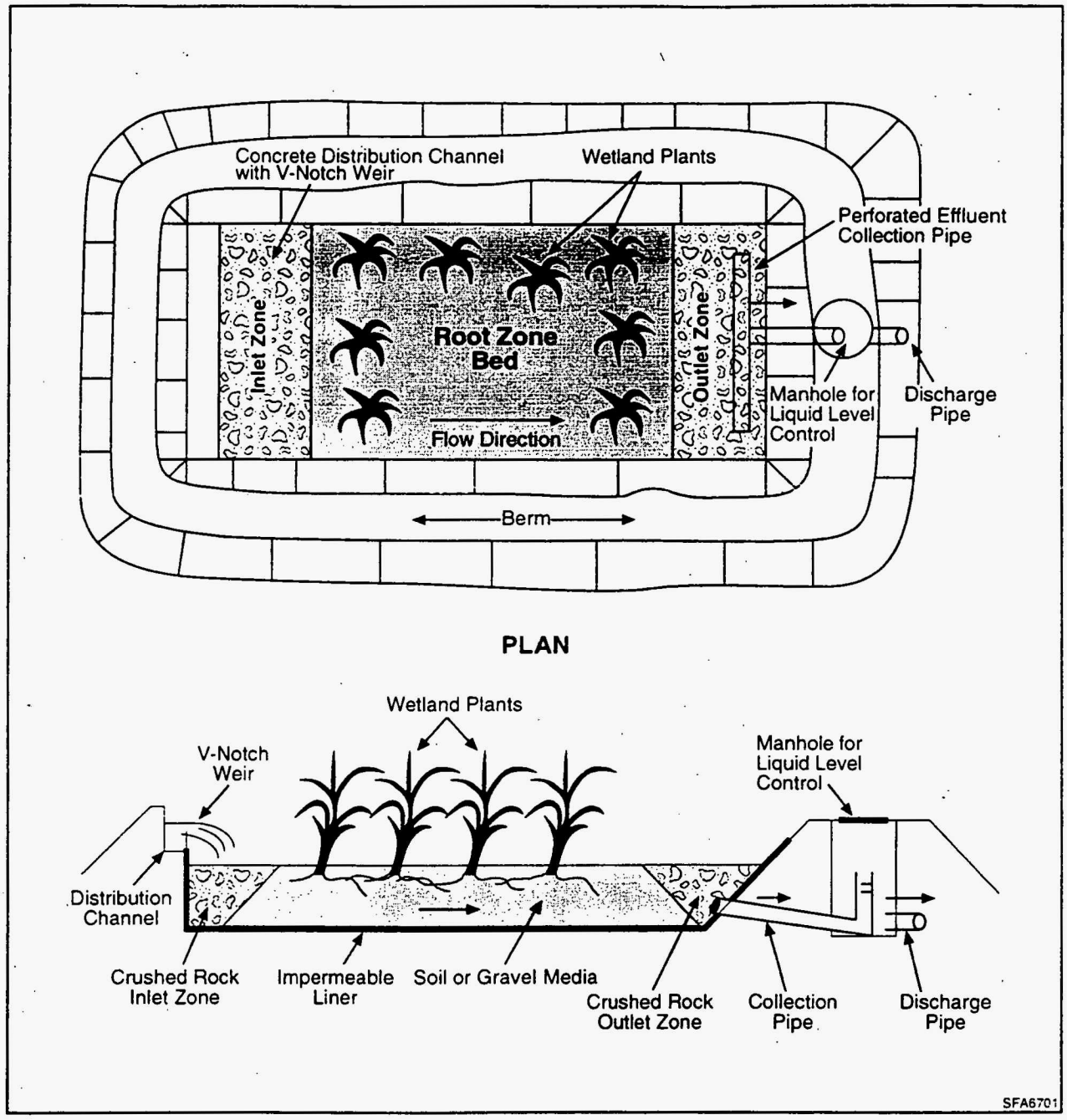

FIGURE 3.5 Typical Root Zone Bed (Source: Conley et al. 1991)

distribute the groundwater across the constructed wetland. From the inlet zone, groundwater flows through soil or gravel media where it is treated by phytoremediation. Effluent is collected in the outlet zone, which resembles the inlet zone with the addition of a perforated pipe installed at the bottom to facilitate collection and discharge of the effluent. The water level in the root zone bed where phytoremediation occurs is controlled by a flow-control device, such as the standpipe in a manhole illustrated in Figure 3.5. Automatic sampling devices can be included as part of a monitoring system, and fencing and screens can be provided to limit contact of contaminated groundwater by terrestrial animals and waterfowl. Operations involve primarily fertilization and watering, if necessary, to maintain plant growth. Other activities include monitoring nutrient concentrations, water levels, and plant growth, and removal of any invading species and weeds. Harvesting, disposal of contaminated plant mass, and repeating the plant growth cycle are necessary for plants involved in heavy metal remediation (i.e., uranium removal). Replanting is performed as necessary.

The two constructed wetlands for the WSCP and the WSOW would have the capacity to treat between 760 and 2,400 L/min (200 and 620 gpm) and between 24 and 72 L/m (6 and 19 gpm), respectively, of extracted groundwater and would have total footprints of between approximately 18 and 56 ha (44 and 140 acres) at the WSCP and between 0.6 and 2 ha (2 and 5 acres) at the WSOW (Appendix D). (For the WSOW, a total of three wetlands, with a total footprint of 0.3 ha (0.7 acre), might be constructed because of the large distances between the areas of contaminated groundwater. This analysis assumed treatment of WSOW-extracted groundwater at one location. The siting and locations of any constructed facilities would be determined during the remedial design/remedial action phase.) The footprint required for the two constructed wetlands was determined on the basis of assuming an idealized plug flow of the contaminated groundwater in the wetland, a wetland depth of 1 m (3 ft), and first-order kinetics for the reduction of TNT and DNT concentrations with time (Medina and McCutcheon 1996; Todd and Lange 1996). This analysis also assumed that the plant-mediated degradation of TNT and DNT would be the rate-limiting steps in the phytoremediation of contaminated groundwater (the removal of TCE from the groundwater would occur primarily by volatilization and not by phytoremediation). The actual design of the phytoremediation system would be determined during the remedial design phase, at which time the necessary flow capacity, required contact time to achieve contaminant concentration reduction, contaminant concentrations likely to

be encountered, and selection of appropriate plant types for the various contaminants would be taken into account.

The sites would continue to perform environmental monitoring to the extent necessary to ensure long-term performance of the remedy. Monitoring for toxic effects on indigenous wildlife (because of drinking the wetland influent) and wildlife control would be part of the annual monitoring program.

3.3.2.7 Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater

Alternative 7 would involve extraction and ex-situ treatment of the groundwater contaminated with TCE to achieve a groundwater concentration of 5 µg/L or less for TCE. An approach identical to that applied in Alternative 2 would be used for managing groundwater not contaminated with TCE. This alternative would actively remediate only TCE.

The objectives and design of Alternative 7 are similar to those for Alternative 3, except that only groundwater exceeding a TCE concentration of 5 µg/L would be removed and treated by this alternative. Groundwater exceeding a TCE concentration of 5 µg/L would be removed using conventional extraction wells, pumped to and treated in an aboveground treatment system consisting of a sequence of physical and chemical unit operations, and released to a permitted discharge point.

A triangular area with an altitude of 120 m (380 ft) and a base of 420 m (1,400 ft) was assumed to be remediated by this method for TCE removal. (The proposed location is shown in Figure 3.6) An average depth of 15 m (50 ft) was assumed, on the basis of hydrogeologic cross-sectional data given in the RI (DOE and DA 1998b), which shows the depth of the shallow (weathered Burlington-Keokuk) aquifer as a function of distance.

Approximately 200 to 650 vertical extraction wells at the WSCP and the WSOW (Appendix C) were assumed to be required to achieve a reasonable extraction rate and to contain further spread of contamination. The wells would be between 16 m (50 ft) and 30 m (100 ft) deep, have a screened length of about 10 m (30 ft), and be 15 cm (6 in.) in diameter. Additional investigation of the shallow aquifer characteristics would be necessary for detailed evaluation of the placement of the extraction wells and estimation of groundwater extraction rates. The actual location,

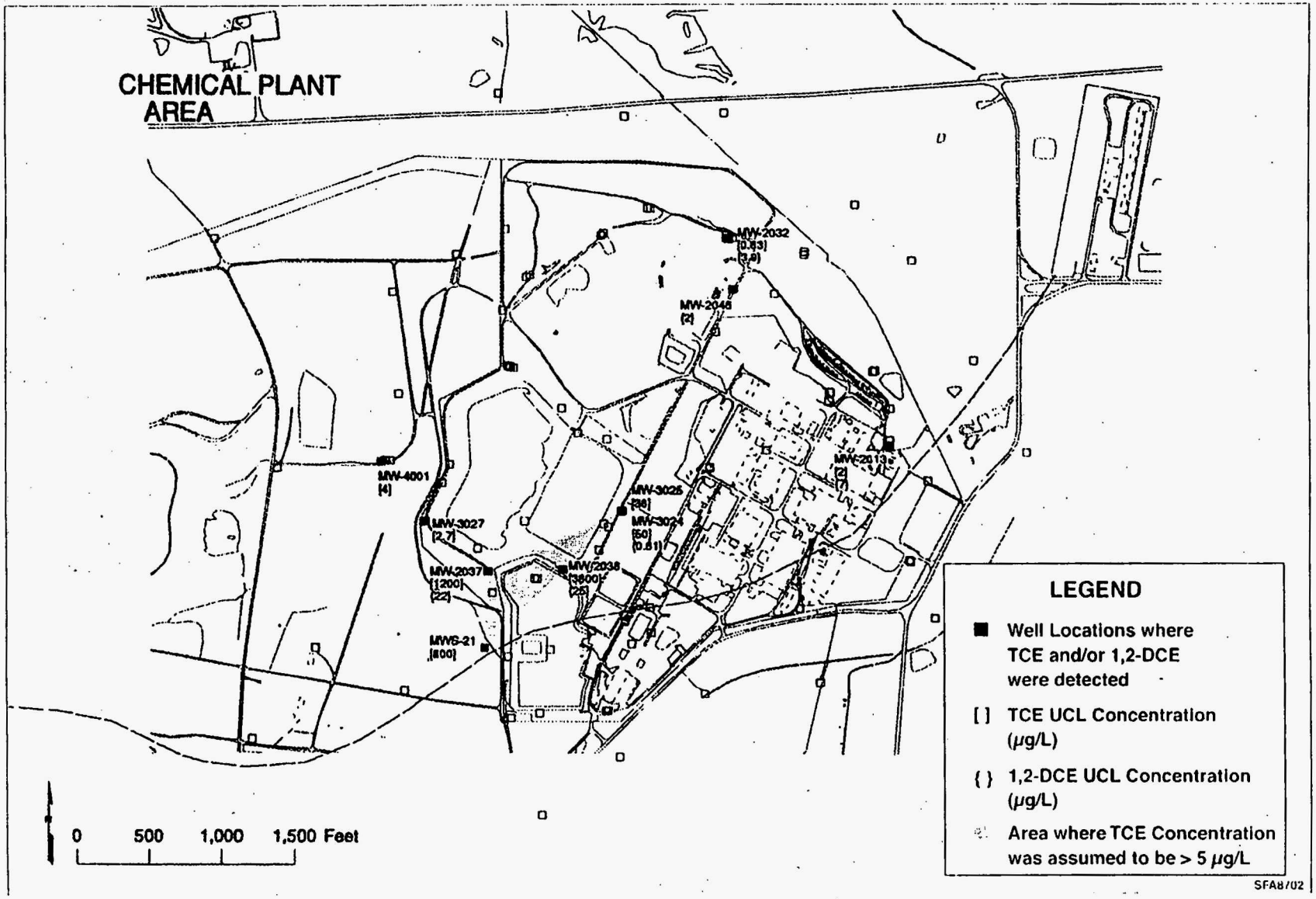

FIGURE 3.6 Area Assumed to be Remediated Using Electrokinetics

size, capacity, and depth of the various extraction wells would be determined during the remedial design phase, at which time the hydrogeologic characteristics (i.e., permeability, thickness of the aquifer, depth of the affected groundwater) and the delineation of the TCE-contaminated area would be taken into account.

Under Alternative 7, a single groundwater treatment facility was assumed to be constructed, with a treatment capacity ranging from 4 to 12 L/s (60 to 195 gpm) and a footprint ranging from 180 to 360 m^2 (1,900 to 3,800 ft^2), depending upon the number of extraction wells required. The preconceptual groundwater treatment process would be similar to that proposed for Alternative 4 and would involve clarification and multimedia filtration to remove any solids collected during groundwater extraction, liquid phase adsorption using GAC to remove TCE and other organics, and reverse osmosis and ion exchange for nitrate removal.

The air would be monitored to detect airborne contamination generated during remedial activities, so that appropriate mitigative measures could be taken. Long-term air monitoring would be implemented following completion of construction to ensure detection of any potential airborne releases of contaminants associated with duct leaks or maintenance of the GAC treatment system. The sites would continue to perform environmental monitoring to the extent necessary to ensure long-term performance of the remedy.

Because contaminated substances would remain on-site in the groundwater at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

After construction of the extraction well network and associated groundwater treatment systems, the two systems would be carefully monitored on a regular basis and their performance evaluated. The time required for in-situ treatment for Alternative 7 is predicted to be 16 years (Appendix C), assuming a maximum TCE concentration of 9,000 µg/L. The actual performance in the field may vary from that assumed during design, given uncertainties about subsurface geology prior to construction and operation.

3.3.2.8 Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping

Alternative 8 involves in-situ treatment of the groundwater contaminated with TCE by using in-well vapor stripping to achieve a groundwater concentration of 5 µg/L or less of TCE. An approach identical to that applied in Alternative 2 would be used to manage the other groundwater contaminants such as the nitroaromatic compounds and nitrates.

In-well vapor stripping technology involves the creation of a groundwater circulation pattern and simultaneous aeration within the vapor stripping well that volatilizes VOCs (in this case, TCE) from the circulating groundwater. (The in-well vapor stripping process in its current stage of development cannot accommodate removing nonvolatile or highly soluble compounds from groundwater.) Air-lift pumping is used to lift groundwater and strip it of contaminants. Contaminated vapors are drawn off for aboveground treatment. Partially treated groundwater is then forced out of the well into the vadose zone, where it reinfiltrates to the water table. Untreated groundwater enters the well at its base and replaces the water lifted through pumping. Eventually, the partially treated water is cycled back through the well through this process until contaminant concentration goals are met (Miller and Roote 1997).

One reported advantage of in-well vapor stripping technology is that it can continuously remove VOCs from groundwater without pumping the water to the surface. Thus, it eliminates the need to handle contaminated water above the ground and to dispose of or store partially treated water. It also eliminates the need to drill expensive injection wells required by other in-situ treatment processes. Other reported advantages of in-well stripping include its lower capital and operating costs, because of the use of a single well for extracting vapors and remediating groundwater, and its simple design, which limits maintenance requirements (Miller and Roote 1997).

In-well vapor stripping technology consists primarily of a screened well submerged beneath the water table and an air line within that well that also extends to below the water table (see Figure 3.7). A compressor delivers air or an inert gas such as nitrogen to the water column, which aerates the water within the well. The gas bubbles cause the water within the well to be less dense than the nonaerated water outside. As a result, the dense water flows in through the well screen and forces the aerated water upward within the well. The result is a rising column of aerated water within the well, which forms an air lift pumping system.

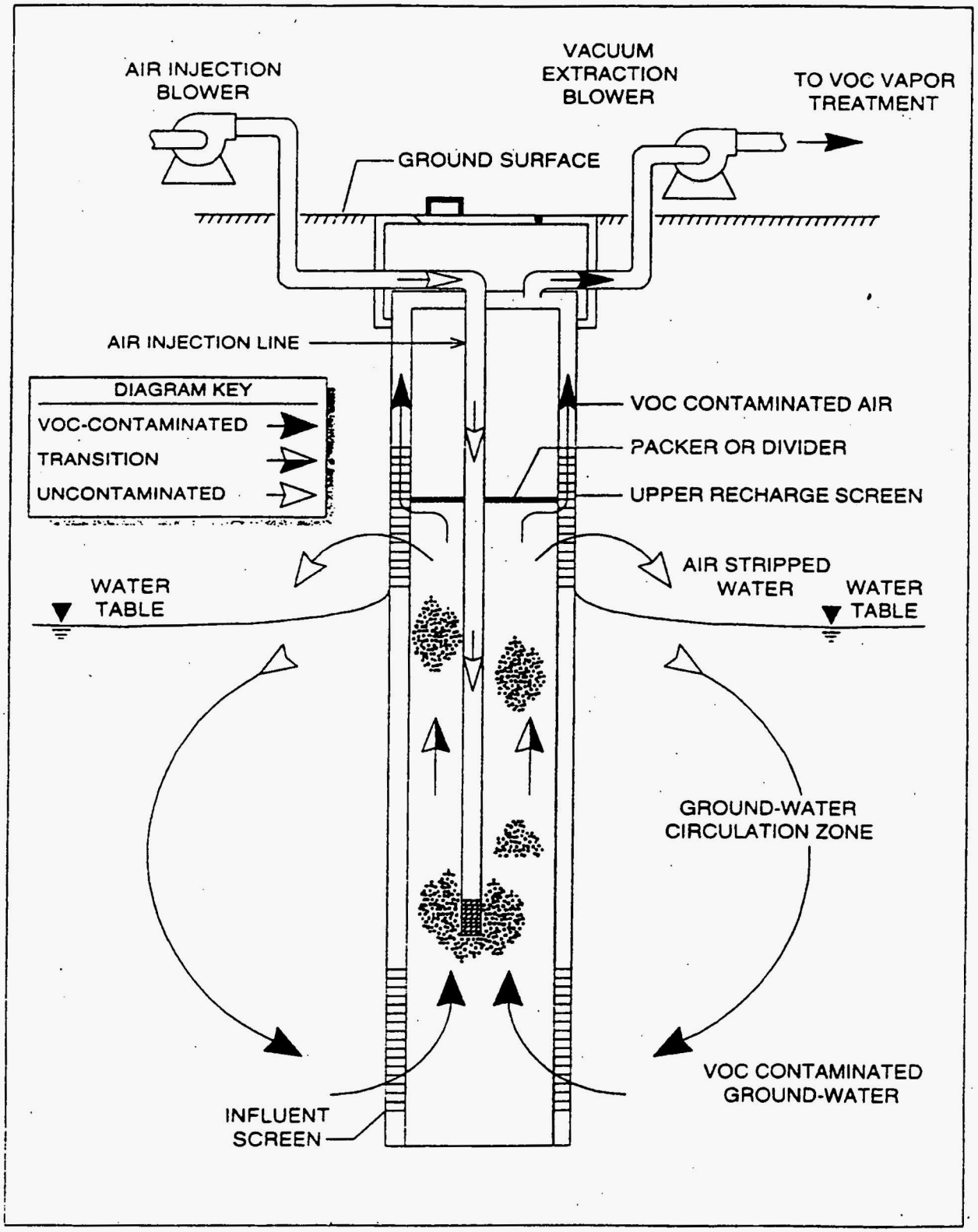

FIGURE 3.7 In-Well Vapor Stripping Process (Source: Miller and Roote 1997)

As the aerated groundwater column rises within the well, the VOCs dissolved in that groundwater will volatilize from the aqueous phase into the vapor phase within the air space of each bubble. The air/water mixture rises until it encounters a packer or deflector plate installed within the well that prevents the passage of rising water or bubbles. When the rising water column hits the packer, the bubbles burst and the entrained vapor is stripped off laterally through the upper vacuum casing along with surrounding soil vapor. The outer casing is under a vacuum, and the vapors are drawn upward through the annular space and collected at the surface for treatment. The groundwater from which some VOCs have been removed reenters the contaminated zone. The laterally deflected water percolates downward through the vadose zone back to the groundwater. Reinfiltrating water creates a toroidal circulation pattern around the well so that waters can be treated through multiple cycles to achieve the desired level of removal. The partially treated groundwater reentering the aquifer is eventually cycled back through the process as groundwater enters the base of the well. Because the VOCs are stripped from the groundwater below the surface, contaminated water is never removed from the ground, thus eliminating the need for wastewater discharge permits.

The circulation of groundwater surrounding the well has been reported to create strong vertical gradients that effectively dislodge residual pore-space contamination [EPA 1996c]. This flushing action enhances and expedites removal beyond results usually obtained by conventional groundwater extraction systems. A large radius of influence per vapor stripping well also gives the technology significant installation and cost advantages over other in-situ treatment technologies such as air sparging.

The in-well vapor stripping treatment system would be constructed by using a drilling rig to install the stripping wells. This analysis assumes a vapor stripping well design composed of a 25-cm (10-in.)–diameter PVC pipe that is screened at two discrete intervals. Similar to Alternative 7, a triangular area with an altitude of 120 m (380 ft) and a base of 420 m (1,400 ft) was assumed to be remediated by this approach under Alternative 8. Preliminary calculations indicate that the successful application of the in-well stripping process would require installation of 9 to 16 vapor stripping wells performed with Schrauf and Pennington's (1995) methodology. The actual design process is proprietary and is based on a series of steps that lead to the development of the geometric and flow parameters governing the system. The actual spacing and design of the remediation system would be determined during the remedial design phase, at which time the following would be taken

into consideration: the radius of influence of a single vapor stripping well, the required number of recirculations of contaminated groundwater through the stripping well, contaminant concentrations likely to be encountered, lithology of the shallow bedrock aquifer, and results of any tracer tests and demonstrations performed in the field.

After the screened intervals are developed, a PVC eductor pipe with a slightly smaller diameter than that of the stripping well would be inserted into the well and would extend from the lower screen to above the upper screen. An air injection line 10 cm (4 in.) in diameter with a diffuser at the lower end would be inserted into the eductor pipe. The upper end of the air line would be attached to an injection blower for pressurized air injection.

An injection blower would supply air down the air line and out the diffuser into the groundwater. Groundwater would enter the lower screen, and aerated water would rise in the eductor pipe. The rising water would hit the packer, flow out of the eductor pipe, and exit through the upper well screen. The treated water would recharge to the vadose zone at a maximum recirculation rate estimated to be approximately 0.1 L/s (2 gpm), on the basis of the methodology given in Schrauf and Pennington (1995). This methodology appears to result in conservative (lower) estimates of the groundwater recirculation rate, when compared with experimentally determined values in the literature (Gvirtzman and Gonen 1995; SBP 1997). Aquifer pumping tests and modeling studies may be necessary to determine the well recirculation rate that would occur under field conditions.

A vacuum blower would be supplied for stripped VOC vapor removal. Once stripped from the groundwater and brought to the surface, the vapors would be removed from the upper well casing by vacuum blower and treated by an off-gas system consisting of gas-phase adsorption using GAC.

Gas-phase adsorption is a natural process in which molecules of a gas are physically attracted to and held at the surface of a solid (Cheremisinoff and Cheremisinoff 1993). Treating waste streams by adsorption involves transferring and concentrating contaminants (the adsorbate) from one medium (gas) to another (the adsorbent). The most commonly used adsorbent is GAC. In gas-phase carbon adsorption, the contaminated gas comes in contact with the carbon by passing through one or more adsorbers, usually the fixed bed type. A fixed bed adsorber is a stationary canister packed with GAC beds. The activated carbon selectively adsorbs organic molecules that are held in the internal micropores of the carbon granules. This analysis assumed that gas phase

adsorption of the TCE vapor stream would be performed by a dual bed packaged treatment system consisting of two carbon adsorbers, a pump. and associated piping configured in series (EPA 1995b). The replacement schedule for the spent carbon absorbers and the total quantity of carbon required due to replacements would depend on the duration of the carbon treatment, the carbon absorber unit chosen, and the number of absorbers. This analysis assumed replacement of the spent carbon every three months. Tests may be performed during the remedial design phase to better define the design of the carbon adsorption system, including the optimum number of canisters.

Prior to gas-phase carbon adsorption, the relative humidity (RH) of the gas stream may need to be lowered for efficient utilization of the activated carbon. At high RH values, most of the pores are filled with water, thereby reducing the capacity of the GAC. As the temperature increases, the RH is reduced; more pores are dried, and capacity increases. An air heater can be used to raise the temperature of the gas stream by 11° to 14°C (20° to 25°F) above ambient. This analysis assumed the installation of explosion-proof hazardous air location heaters that would generally be able to raise the ambient air temperature by 11°C (20°F). The need for a heater would generally be based on the results of a pilot test of the in-well stripping technology.

The air would be monitored during remedial activities so that appropriate mitigative measures could be taken if any airborne contamination was detected. Long-term air monitoring would be implemented following completion of construction to ensure the detection of potential airborne releases of contaminants resulting from system failure during operations. Environmental monitoring would be continued at the sites to the extent necessary to ensure long-term performance of the remedy.

Because contamination would remain on-site in the groundwater at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

After construction of the in-well stripping and associated off-gas treatment systems, the two systems would be carefully monitored on a regular basis, and their performance would be evaluated. The time required for in-situ treatment for Alternative 8 is predicted to range from two to three years, if it is assumed that water can be stripped of 90% of its TCE by one pass through a vapor stripping

well (Cichon et al. 1997; HazTECH 1997) and the maximum TCE concentration is 1,300 µg/L. The actual performance in the field may vary from that assumed during design, given uncertainties about subsurface geology prior to construction and operation.

3.4 CRITERIA FOR SCREENING ALTERNATIVES

As defined in the NCP (EPA 1990a), the development and screening of the remedial alternatives should be guided by three criteria: effectiveness, implementability, and cost. Effectiveness focuses on (1) the degree to which an alternative reduces toxicity, mobility, or volume through treatment; minimizes residual risks and affords long-term protection; complies with PRGs; and minimizes short-term impacts; and (2) how quickly the alternative achieves protection. Both short-term and long-term effectiveness are evaluated. Short-term effectiveness refers to the active remediation period when construction and implementation activities are performed; long-term effectiveness refers to the period after the remediation activities have been performed.

Implementability focuses on the technical feasibility and availability of the technologies needed for an alternative and the administrative feasibility of implementing that alternative. Timeliness of implementation, potential interference with site operations, and potential future maintenance needs are also assessed as secondary factors.

The cost criterion considers the costs of construction and any long-term costs to operate and maintain an alternative. A general cost analysis is to be applied to identify alternatives that are significantly more expensive than other alternatives that achieve the same level of risk reduction (EPA 1988b). Costs considered in this screening process are only approximate, and an alternative is screened out if it is clearly an order-of-magnitude more expensive than other alternatives that provide the same apparent degree of protection. Costs considered in this screening process are only approximate, and costs that are grossly excessive compared to the overall effectiveness of alternatives may be considered as one of several factors used to eliminate alternatives. Alternatives providing effectiveness and implementability similar to that of another alternative by employing a similar method of treatment or engineering control, but at a greater cost, may also be eliminated.

3.5 SCREENING OF PRELIMINARY ALTERNATIVES

3.5.1 Alternative 1: No Action

Alternative 1 — which effectively is no further action over any remedial action that has already occurred or is projected to occur — is described in Section 3.3.2.1. The no action alternative provides a baseline for comparison with the other alternatives.

3.5.1.1 Effectiveness

Alternative 1 would provide no additional reduction in risk to human health posed by the contaminated groundwater, other than through natural processes — including reduction of the nitroaromatic compounds and TCE by biodegradation and sorption and attenuation of the uranium by decay, sorption, precipitation, and dilution of the contaminated groundwater with rainwater and runoff. Alternative 1 would allow for the possible continued migration of the contaminants and potential further degradation of the groundwater within the WSCP and the WSOW. There would be no reduction in toxicity, mobility, or volume of the contaminated groundwater because no treatment would be involved, and there would be no short-term impacts to members of the public, workers, or the environment during construction or implementation because no remedial action would be conducted. Alternative 1 would not prevent the use of contaminated groundwater. Under current land use conditions, the contaminated groundwater at the WSCP and the WSOW is not accessed and used and, therefore, poses no imminent risk to human health or the environment. Likely future land use is expected to be similar to current land use. However, concentrations of groundwater contaminants could result in potential unacceptable risk if access and use occurred more frequently than is currently the case for recreational visitors. Therefore, under Alternative 1, protection of human health and the environment in the extended future could not be verified because all monitoring activities would end.

3.5.1.2 Implementability

No implementability concerns would be posed by Alternative 1 because no action would be taken nor would any future activities be considered. No technologies or management strategies

would be implemented, nor would any permits, licenses, or approvals associated with undertaking a remedial action be needed.

3.5.1.3 Cost

No net present worth, capital, or annual O&M costs would be associated with the no action alternative because no activities would be undertaken.

3.5.2 Alternative 2: Monitoring with No Active Remediation

Alternative 2 would involve the implementation of routine sampling and analyses to monitor the possible continued migration of the contaminants and the potential construction of new monitoring wells. This alternative is described in Section 3.3.2.2.

3.5.2.1 Effectiveness

Alternative 2 might be protective of human health and the environment over the long term because monitoring and investigative activities by the DOE and DA would enable identification of any potential further contaminant migration and any variations in local geochemical conditions (such as Eh and pH) that could adversely affect removal of the contaminants from the groundwater by precipitation, biodegradation, and other natural processes. Such activities would verify that remediation goals were being met within a reasonable time period and that the contaminant distribution in the water-bearing zone was being tracked. Response measures would be considered if data indicated future migration of residual contamination would result in unacceptable exposure concentrations at potential locations of existing or foreseeable receptors. (Possible contingency measures are described in Section 3.3.2.2.) Therefore, unacceptable impacts to human health and the environment would not be expected to occur.

Deed restrictions could be used to prevent the installation of new wells in the area of contaminated groundwater, thereby reducing the potential risk to human health associated with ingestion or inhalation of groundwater contaminants by limiting exposure. These restrictions would, however, be difficult to enforce without application of additional controls. Continued federal ownership would eliminate the potential risks associated with on-property groundwater, but not those associated with off-property groundwater.

Alternative 2 would have the least potential short-term environmental impacts among any of the action alternatives. The short-term impacts associated with this alternative would be the physical hazards to workers during monitoring well construction and operations, minor criteria pollutant emissions during any construction activities, and disturbance of soil and the resulting dust emissions. Appropriate mitigative measures would be enacted during construction and operations to protect workers and members of the public. The air would be monitored to ensure that the controls were working. Protective equipment would be used, and dust suppression methods would be enacted to minimize short-term risks to workers.

If long-term groundwater monitoring were discontinued, contaminants could potentially migrate off property without prior detection. Transport modeling of TCE was conducted with the analytical solute transport model BIOSCREEN (EPA 1996a) by using the recommended first-order biodegradation rate option. The results suggest that natural processes would likely reduce TCE concentrations below remediation goals before off-site receptors were reached, primarily because of dilution and biodegradation (Appendix E). Although uncertain, these results suggest that active remediation might not be necessary.

For Alternative 2 to remain effective over the long term, careful consideration would have to be given to long-term monitoring, maintenance, and control for a reasonable period (i.e., 10 years). Because this alternative would leave contaminants on-site at concentrations above health-based levels, a review would have to be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

Alternative 2 would not satisfy the statutory preference for treatment as a principal element of remediation, and there would be no reduction in toxicity, mobility, or volume of the contaminated groundwater through treatment. Residual contamination would remain high in the short term. However, the concentrations of groundwater contaminants at the WSCP and the WSOW have decreased with time because source control has already been provided through removal, treatment, and storage and disposal of materials that could release contaminants to groundwater (through remediation of contaminated soil, removal of contaminated structures, construction of berms around the raffinate pits at the WSCP to eliminate surface runoff, and dewatering of the raffinate pits). Concentrations have also decreased due to infiltration of uncontaminated groundwater from

rainwater and runoff and through natural processes such as adsorption to soil particles, biodegradation, and chemical reactions with subsurface materials.

3.5.2.2 Implementability

Few implementability concerns would be posed by Alternative 2 because of the limited actions required. The proposed monitoring would provide warning of failure before significant exposure occurred. Therefore, taking additional actions prior to significant exposure would be relatively easy to implement.

Monitoring contaminant migration could easily be carried out by the DOE and DA. No special equipment or specialists would be required to implement Alternative 2 other than what is commonly associated with the construction and operation of groundwater monitoring networks. Procedures would be available to determine the presence of contaminants in groundwater samples drawn from the monitoring wells. Construction of any proposed monitoring wells would require mobilization of a drilling rig for installation; such equipment is readily available. Resources required for maintenance of the existing and proposed groundwater monitoring systems would also be readily available. Implementation of institutional controls would require only administrative effort and legal enforcement. Continued federal ownership would be easy to implement because it would provide continuation of the existing situation. No permits or licenses would be required to implement Alternative 2. Registration of any installed monitoring wells with the State of Missouri would be required.

3.5.2.3 Cost

The estimated cost of Alternative 2 is relatively low; it would be the least expensive of all the action alternatives. In general, expenses associated with institutional control and monitoring would be low. Capital expenses would include the construction of any monitoring wells and routine replacement of existing equipment for groundwater monitoring. Given the low replacement costs compared with the capital cost for monitoring well installation, the cost of routine equipment replacement was not considered. On the basis of this preconceptual design and the application of cost factors specific to the Weldon Spring site for indirect activities, the capital cost of Alternative 2 is estimated to be approximately $0.3 million (Appendix F).

Annual expenses would be incurred for the groundwater monitoring program. The annual cost of operating the proposed monitoring wells was estimated on the basis of the current costs for the existing monitoring well network, assuming that existing wells would be sampled annually. The annual O&M cost is estimated to be approximately $0.3 million. Per EPA guidance, the annual costs were discounted to a current value using a discount rate of 7% (before taxes and after inflation) (EPA 1993) and a time period of 30 years (EPA 1988a). The 30-year present worth of Alternative 2 is estimated to be approximately $4.8 million, which is the lowest of all the action alternatives.

The costs associated with potential future actions (e.g., in the event that migration of residual contamination would result in unacceptable exposure concentrations) were not quantified because the uncertainty associated with these future activities precludes accurate assessment of costs.

3.5.3 Alternative 3: Natural Attenuation

Alternative 3 would consist of the implementation of routine sampling and analyses to verify and monitor natural remediation processes and the potential construction of new monitoring wells. This alternative is described in Section 3.3.2.3.

3.5.3.1 Effectiveness

Alternative 3 would be similar to Alternative 2 in protecting human health and the environment over the long term. Unacceptable impacts to human health and the environment are not expected to occur.

The potential short-term environmental impacts associated with Alternative 3 are few, but more than those associated with Alternative 2 because of the construction and operation of 15 additional monitoring wells. The short-term impacts associated with Alternative 3 would be the physical hazards to workers during site sampling and any monitoring well construction and operations, minor emissions of criteria pollutants during any construction, and disturbance of soil and resulting airborne dust emissions. Appropriate mitigative measures would be enacted during construction and operations to protect workers and members of the public. The air would be monitored to ensure that the controls were working. Protective equipment would be used, and dust suppression methods would be enacted to minimize short-term risks to workers.

Deed restrictions could be used to ensure that no new wells would be installed in the area of the contaminated groundwater, thereby reducing, by limiting exposure, the potential risk to human health associated with ingestion or inhalation of groundwater contaminants. These restrictions would, however, be difficult to enforce without application of additional controls (e.g., fencing). Continued federal ownership would reduce the potential risks associated with on-property groundwater but not those associated with off-property groundwater.

For Alternative 3 to remain effective over the long term, careful consideration would have to be given to long-term monitoring for a reasonable period (i.e., greater than 10 years). Because this alternative would leave contaminants on-site at concentrations above health-based levels, a review would have to be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

Alternative 3 would not satisfy the statutory preference for treatment as a principal element of remediation and would not result in reduction in toxicity, mobility, or volume of the contaminated groundwater through treatment. Residual contamination would remain high in the short term, but the concentrations of contaminants at the WSCP and the WSOW have already decreased with time. This has occurred as the result of source-control in the form of treatment of materials that might release contaminants to groundwater (through remediation of the contaminated soil, removal of contaminated structures, construction of berms around the raffinate pits at the WSCP to eliminate surface runoff, and dewatering of the raffinate pits); infiltration from rainwater and runoff; and natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials.

3.5.3.2 Implementability

One implementability issue for Alternative 3 would be associated with determining site-specific biodegradation rates. These rates must be determined because biodegradation is considered to be the dominant contaminant degradation process for natural attenuation. A site-specific biodegradation rate would be required for all COCs; these rates would be compared with the rates of contaminant transport and natural attenuation to assess whether natural attenuation would degrade contaminants to acceptable levels. Evidence exists indicating that DNT will degrade under the groundwater conditions present at the WSOW shallow aquifer (Bradley et al. 1997). Laboratory

"microcosm" studies might have to be developed to simulate aquifer conditions and to demonstrate that native bacteria could create the necessary biochemical reactions to destroy the COCs other than DNT. In some cases, these data might be inconclusive or ambiguous because of technical difficulties in collecting data in the field (Odermatt 1997). Nearly complete removal of TNT can be achieved in several months from microbial degradation under laboratory conditions (Bradley and Chapelle 1995); however, the rates of degradation of nitroaromatic compounds are expected to be slower in the field (see Section 3.3.2.2). Thus, laboratory studies, which are generally time-consuming and expensive, might not provide adequate documentation that biodegradation was taking place or quantify the biodegradation rate.

Another implementability issue for Alternative 3 is the development of a three-dimensional representation of the site's hydrogeologic and contaminant transport system. Simulation of natural attenuation requires using analytical or numerical solute fate and transport modeling. These data would be used to determine whether natural attenuation was sufficient to prevent contaminant migration from completing exposure pathways in concentrations above applicable regulatory or risk-based corrective action standards. (Thus, determining the potential decrease in contaminant concentrations currently on-site, assuming no groundwater movement, would not account for potential contaminant transport to off-site receptors or establish whether natural attenuation processes would reduce contaminant concentrations to below unacceptable risk levels.) Transport modeling of the shallow aquifer on a three-dimensional basis would be difficult because of the high temporal variation in the groundwater flow regime (see Section 3.3.3.2). Two regimes of groundwater flow are postulated to exist in the shallow bedrock aquifer: diffuse flow and high-velocity turbulent flow occurring in conduits and in large, isolated fractures. Diffuse flow follows Darcy's law for a porous medium, but turbulent flow does not. Accurate representation of site conditions would require consideration of both flow regimes. Two models might have to be developed; one model would assume a groundwater flow system dominated by porous media, and the other would assume a system dominated by fracture flow.

Monitoring would provide notice of failure before significant exposure occurred, which would allow additional actions to be taken prior to significant exposure. Contaminant migration could easily be monitored; no special equipment or specialists would be required beyond what is already available at the sites. Existing analytical procedures could be used to determine the presence

of contaminants (such as nitroaromatic compounds) in groundwater samples drawn from the monitoring wells. However, new procedures might have to be developed for sampling and analysis of parameters used to determine the extent of contaminant degradation (e.g., nutrients and electron acceptors such as dissolved oxygen). Construction of any proposed monitoring wells would require mobilization of a drilling rig for installation; however, such equipment is readily available. Resources required for maintenance of the existing and proposed groundwater monitoring systems should be readily available. Implementation of institutional controls would require only administrative effort and legal enforcement. Continued federal ownership would be easy to implement because it would provide continuation of the existing situation. No permits or licenses for on-site activities would be required to implement Alternative 3. Registration of any installed wells with the State of Missouri would be required.

3.5.3.3 Cost

The cost would be slightly higher for Alternative 3 than for Alternative 2. Using engineering judgment, it was assumed that the cost for additional subsurface sampling and sample analysis to confirm contaminant degradation rates and cleanup status would be similar to the cost of a remedial investigation for the WSCP and the WSOW. On the basis of this preconceptual design and application of cost factors specific to the DOE Weldon Spring site for indirect activities, the capital cost of Alternative 3 was estimated to be approximately $0.7 million (Appendix F). The capital cost would be primarily for proposed monitoring well construction.

Annual expenses would be incurred from the groundwater monitoring program. The annual cost of operating the proposed monitoring wells was estimated on the basis of current costs for the existing monitoring well network, assuming that existing wells would be sampled annually. It was also assumed that the field investigations to verify and monitor natural remediation processes would be performed over a five-year period, and that these costs would be included as an annual O&M cost. The annual O&M cost was estimated to be between $1 and $2 million (Appendix F). Assuming a discount rate of 7% per year, the 30-year present worth of Alternative 3 would be approximately $10 million (Appendix F).

The costs associated with potential future actions (e.g., in the event that migration of residual contamination resulted in unacceptable exposure concentrations) were not quantified

because the uncertainty associated with these future activities precludes accurate assessment of these costs.

3.5.4 Alternative 4: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using Granular Activated Carbon

Alternative 4 would involve extraction of contaminated groundwater using vertical wells and treatment on-site of the TCE and nitroaromatic compounds using GAC treatment. This alternative is described in Section 3.3.2.4.

3.5.4.1 Effectiveness

Alternative 4 would protect human health and the environment by remediating the contaminated groundwater in the shallow bedrock aquifer so that when the remediation was complete, the contaminant concentrations in the groundwater would be below PRGs. In addition, contaminant migration would be largely halted upon implementation of this alternative, and any potential future large-scale contamination of the nearby springs would be effectively prevented. Alternative 4 might be expected to attain all PRGs when remediation was complete. Installation has been estimated to take approximately two to three years.

Alternative 4 would reduce the volume of contaminants through treatment and would afford long-term protection. After remediation was complete, no long-term action would be required.

The short-term impacts associated with Alternative 4 would include the following:

- Physical hazards to workers during installation of the extraction wells, construction and operation of the groundwater treatment facilities, and operation of the monitoring systems;
- Criteria pollutant emissions during construction;
- Disturbance of soil during site clearing, excavation, and regrading for construction of the groundwater treatment facilities and the resulting dust emissions; and
- Off-site transport of spent carbon.

Appropriate mitigative measures would be enacted during construction and operations to protect workers and members of the public. Special safety precautions would be maintained during removal and handling of the spent carbon contaminated with explosive because spontaneous combustion could potentially occur at certain conditions of temperature and humidity (EPA 1995b). Engineering controls such as spraying water for dust suppression would be used to minimize short-term risks to the public, and the air would be monitored to verify that the controls were working. Protective equipment and dust suppression methods would be used to minimize short-term risks to workers. More short-term impacts would result from Alternative 4 than from Alternative 5 because of the off-site transport of spent carbon for disposal purposes.

3.5.4.2 Implementability

The groundwater extraction and treatment technology associated with Alternative 4 has been widely used and found reliable if properly constructed and maintained. However, there are a number of implementability concerns posed by this alternative for this application.

Although groundwater extraction using vertical wells is a relatively mature technology with a history of operating experience, it is generally not applicable when contaminated groundwater migrates into formations from which the groundwater cannot easily be removed, such as fractured bedrock or karst aquifers. The heterogeneous nature of the shallow bedrock aquifer might preclude extraction rates sufficient to attain performance goals. In addition, conventional groundwater treatment is not effective in areas with low permeability (less than 1×10^{-4} cm/s); formations with a high degree of secondary permeability, such as fractured bedrock; and low-solubility contaminants that tend to absorb in the subsurface media (Roote et al. 1997). Drawdown pump test studies might be needed to determine long-term sustainable pumping rates for various points at the WSCP and the WSOW.

Other implementability issues would be associated with conventional extraction. Such issues would include the generation of substantial amounts of wastewater requiring treatment prior to discharge, high energy costs for pumping and moving large volumes of water (which might require additional site infrastructure to supply the necessary electricity), indiscriminate removal of all groundwater components (including those with concentrations below health-based levels), and general slow progress toward terminal regulatory goals due to technical limitations.

A major implementability issue would concern the extraction of TCE-contaminated groundwater. The proposed groundwater extraction system might not be effective for aquifer restoration to ARARs for TCE. Significant amounts of data have indicated that conventional technologies, such as pump and treat, were ineffective in treating groundwater contaminated with TCE.

A major potential concern for Alternative 4 would involve the location of the proposed extraction well network and its potential impact on the future use of the WSCP. A disposal cell is currently being built on-site, which will occupy much of the total WSCP area. Installation and operation of the extraction well network within the WSCP might delay construction and operation of the on-site disposal cell for the time period of active extraction.

Absorption by activated carbon has a long history of use as a treatment process and is a proven technology with documented performance data. An implementation concern would be associated with loading and concentrating explosive compounds on the carbon bed. Proper disposal of the explosives-contaminated carbon would be necessary and could be costly.

No special equipment would be required to implement Alternative 4. It might, however, become necessary to conduct detailed studies to determine whether the performance of the proposed vertical extraction well network would achieve acceptably low concentrations in the groundwater, given the underlying lithology at the WSCP and the WSOW. Vendor expertise would be required for carbon selection because the type and pore size of the carbon, as well as operating temperature, would affect process performance. Bench tests using a groundwater sample from the WSCP and the WSOW might be needed to estimate the carbon usage rate and optimal contact time because the presence of multiple contaminants could impact process performance.

Resources required for maintenance and monitoring should be readily available. The replacement of spent carbon would require an engineer and/or company technician to supervise the operation. Depending on the design, replacement of the spent carbon could take from 1 to 12 hours, with an average time of 6 hours. Resources required for maintenance of the groundwater extraction and product pumps and associated controls should be readily available. Pump maintenance and repair would generally be needed every 18 months. The only other requirement would be maintenance of

the groundwater monitoring wells, which is currently an ongoing activity that does not require any additional special equipment or personnel.

A major implementability concern for Alternative 4 would be the active life of the groundwater treatment facilities, which is generally about 30 to 35 years. Three to four equivalent plant lifetimes of treatment capacity or more might be required to meet the estimated treatment duration of at least 100 years for extraction of 2,4-DNT-contaminated groundwater. The technical feasibility of this aspect of Alternative 4 is uncertain given the potential number of replacement facilities that would be required if conventional extraction of 2,4-DNT was applied.

To allow discharge of the treated water to the Missouri River, the groundwater treatment facilities at the WSCP and the WSOW would have to meet the substantive requirements and standards of Missouri NPDES regulations. Monitoring of the treated groundwater prior to its release to the Missouri River would be required to ensure compliance with state discharge regulations.

3.5.4.3 Cost

The estimated cost of Alternative 4 is slightly lower than that of Alternative 5. On the basis of the preconceptual design and application of cost factors for indirect activities, the capital cost of Alternative 4 is estimated to be approximately between $41 million and $12 million (Appendix F). The capital cost would be primarily for installation of the approximately 330 to 1,000 extraction wells.

The annual O&M cost is estimated to be between approximately $2 million and $4 million per year (Appendix F). The annual O&M costs would be primarily for groundwater extraction and treatment. Assuming a discount rate of 7% per year, the 30-year present worth of Alternative 4 is estimated to be approximately $53 million to $140 million (Appendix F), much greater than that for Alternative 2 or 3.

3.5.5 Alternative 5: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using UV Oxidation

Alternative 5 would consist of extracting contaminated groundwater using vertical wells and treatment on-site of the TCE and nitroaromatic compounds using UV oxidation. This alternative is described in Section 3.3.2.5.

3.5.5.1 Effectiveness

The effectiveness of Alternative 5 would be similar to that of Alternative 4, except that special safety precautions would be maintained during handling and storage of H_2O_2, and off-site shipment and disposal of spent carbon would not be necessary.

3.5.5.2 Implementability

UV oxidation is currently being used for wastewater treatment, however, a number of implementability concerns would be posed by Alternative 5 at this location. The potential difficulties associated with groundwater extraction would be similar to those discussed for Alternative 4.

One implementability issue for Alternative 5 would be the fact that UV oxidation is an innovative groundwater treatment technology that has been used in full-scale groundwater treatment applications for only 12 years. As of 1994, UV oxidation was in operation in 15 full-scale remedial applications; the majority of these applications were based on groundwater contaminated with petroleum products or industrial solvent-related organics (such as TCE and vinyl chloride) (Marks et al. 1994). Another concern would be the possible formation of intermediate compounds that would be more hazardous and less reactive to UV oxidation. Pilot-scale and/or treatability studies might be necessary to ensure that UV oxidation could successfully reduce contaminant levels for the groundwater within the shallow bedrock aquifer. One disadvantage of UV oxidation would be its high electrical consumption, which might impose limits on the basis of the availability of needed electrical capacity.

UV oxidation is an innovative technology, and special equipment in the form of the UV oxidation unit would be needed to implement this alternative. Specialists might be required to establish the proper UV system design parameters — for example, UV radiation source (i.e., high or low intensity) and UV system design (i.e., whether to use ozone generation, H_2O_2, and/or cavitation in the formation of hydroxyl radicals and in direct photolysis of some contaminants). It might become necessary to conduct detailed studies to determine whether the performance of the proposed vertical extraction well network would achieve acceptably low concentrations in the groundwater, given the underlying lithology at the WSCP and the WSOW.

Resources required for maintenance and monitoring should be readily available. A typical UV oxidation unit requires about 2 to 10 hours each week for maintenance, including daily checks. Resources required for maintenance of the groundwater extraction and product pumps and associated controls should be readily available. Pump maintenance and repair would generally be necessary every 18 months. The only other requirement would be maintenance of the groundwater monitoring wells, which is currently an ongoing activity that does not require any additional special equipment or personnel.

A major implementability concern for Alternative 5 would be the active life of the groundwater treatment facilities, which is generally about 30 to 35 years. Three to four equivalent plant lifetimes of treatment capacity or more might be required to meet the estimated treatment duration of at least 100 years for extraction of 2,4-DNT-contaminated groundwater. The technical feasibility of this aspect of Alternative 5 appears uncertain, given the potential number of replacement facilities that would be required if conventional extraction of 2,4-DNT was applied.

To allow discharge of the treated water to the Missouri River, the groundwater treatment facilities at the WSCP and the WSOW would have to meet the substantive requirements of Missouri NPDES regulations. Monitoring of the treated groundwater prior to its release to the Missouri River would be required to verify compliance with state discharge regulations.

3.5.5.3 Cost

The estimated cost of Alternative 5 is slightly higher than that of Alternative 4. Costs for UV oxidation are generally higher than competing technologies because of energy requirements (Marks et al. 1994). On the basis of the preconceptual design and application of cost factors specific to the Weldon Spring site for indirect activities, the capital cost of Alternative 5 is estimated to be approximately between $42 million and $120 million (Appendix F). The capital cost would be primarily for the installation of 330 to 1,000 extraction wells.

The annual O&M cost is estimated to be between approximately $2 million and $4 million per year (Appendix F). The O&M costs for UV oxidation would be affected by the groundwater characteristics, treatment process design (lamp maintenance and oxidant dosage costs), and operations. The annual O&M costs would be primarily for groundwater extraction and treatment. Assuming a discount rate of 7% per year, the 30-year present worth of Alternative 5 is estimated to

be between approximately $54 million and $140 million (Appendix F), higher than that for Alternative 4.

3.5.6 Alternative 6: Groundwater Removal, On-Site Treatment Using Phytoremediation

Alternative 6 would consist of extracting contaminated groundwater using vertical wells and treatment on-site using phytoremediation. This alternative is described in Section 3.3.2.6.

3.5.6.1 Effectiveness

Alternative 6 would protect human health and the environment by remediating the contaminated groundwater in the shallow bedrock aquifer so that when the remediation was complete, the contaminant concentrations in the groundwater would be below PRGs. In addition, contaminant migration would be largely halted upon implementation of this alternative, and any potential future large-scale contamination of the aboveground springs would be effectively prevented. Alternative 6 might be expected to attain all PRGs when remediation was complete. Wetlands construction has been estimated to take about one to two years.

Alternative 6 would reduce the volume of contaminants through treatment and would afford long-term protection. After remediation was complete, long-term action might not be required. One long-term indirect benefit to be considered would be the development of additional wetlands that could be released for public use after active remediation was complete. These wetlands could potentially be used for green space, wildlife habitat, and recreational and educational areas. The decision regarding removal of the constructed wetlands following completion of the groundwater treatment would be determined in collaboration with the regulators.

The short-term impacts associated with Alternative 6 would include the following:

- Physical hazards to workers during installation of the extraction wells, construction and operation of the constructed wetlands, and operations of the monitoring systems;
- Criteria pollutant emissions during construction; and

- Disturbance of soil (during site clearing, excavation, and regrading during construction of the constructed wetlands) and the resulting airborne dust emissions.

Appropriate mitigative measures would be enacted during construction and operations to protect workers and members of the public. Engineering controls, such as spraying water for dust suppression, would be used to minimize short-term risks to the public. The air would be monitored to verify that the controls were working. Because of the potential for contaminant release during cultivation and planting, protective equipment and dust suppression methods would be enacted to minimize short-term risks to workers. Fewer short-term impacts would result from Alternative 6 than from Alternative 4.

The operational duration for Alternative 6 would be expected to be the longest among all alternatives involving active remediation because of the curtailment of active remediation during winter.

3.5.6.2 Implementability

Phytoremediation is commonly used to treat wastewater; however, a number of implementability concerns would be posed by Alternative 6 at this location. The potential difficulties associated with groundwater extraction would be similar to those discussed for Alternative 4.

A major implementability concern for Alternative 6 would be the uncertainty concerning whether phytoremediation could sufficiently reduce the contamination to meet EPA cleanup targets for drinking water. The possibility exists for the binding or complexation of some of the contaminants with the exudates and their subsequent transport by the groundwater through the constructed wetland without further contaminant reduction; therefore, research would be required to find suitable plants for further investigation. Bench-scale and pilot-scale testing would then be conducted of the promising plant species; groundwater samples would be taken from the WSCP and the WSOW.

One implementability concern would be the relative newness of phytoremediation compared with the other technologies. Field investigations would be necessary before phytoremediation could be applied at the Weldon Spring site.

This analysis assumed that concurrent phytoremediation of nitroaromatic compounds and chlorinated organics such as TCE would be possible within a single constructed wetland. However, a plant designed to phytoremediate one contaminant might be inhibited by the presence of a different contaminant. Research would have to be conducted prior to the remedial design/remedial action phase with samples of extracted groundwater from the WSCP and the WSOW to ensure the successful implementation of Alternative 6.

A key design consideration and potential implementability concern would be associated with avoiding recontamination of the groundwater because of failure of the liner. Additional design features such as multiple liner systems and/or subsurface drains might be necessary.

Another implementability concern for Alternative 6 would involve the control of animals drinking water from the wetland or feeding on wetland plants. At the influent of the wetland, contaminant removal would be limited; thus, there might be a potential adverse effect on the food chain that could occur if insects and small rodents ate the plants that were collecting the contaminants and these organisms were then eaten by larger mammals. Control of wildlife might be necessary, which could be difficult given the large estimated area of the proposed constructed wetlands.

Information is lacking with regard to whether contaminants can collect within the plants and be released from the plants after harvesting. Development of proper handling and the potential requirement for disposal have not been resolved from a regulatory point of view.

Phytoremediation is generally applied under warmer climates, which allows continuous remediation throughout the year. The potential application of phytoremediation at the Weldon Spring site might be limited in this respect.

Among the many variables involved in using constructed wetlands would be temperature. When the temperature drops below a certain point, wetland plants cease to take up nutrients and die, and microbial activity drops off considerably as well. For this reason, a constructed wetland would not provide the same level of treatment year-round. Seasonal variation in the performance of Alternative 6 would have to be established through field testing.

Another implementability issue for Alternative 6 would concern how well the plant species identified for contaminant degradation (e.g., parrot feather and Eurasian water milfoil for nitroaromatic degradation) would adapt climatically to the Weldon Spring site.

No special equipment or specialists would be required to implement Alternative 6 after completion of any bench-scale and pilot-scale testing. Phytoremediation typically uses the same equipment and materials common to agricultural practice. The constructed wetlands system could be operated by a single low-level technical person on a part-time basis (typically 10% of the time to operate the wetlands system and for any cultivation and planting).

Resources for maintenance and monitoring should be readily available. Maintenance would require about one hour per month. No significant infrastructure would be required other than basic chemical and biological laboratory analyses of water and plant samples. Resources required for maintenance of the groundwater extraction and product pumps and associated controls should be readily available. Pump maintenance and repair would generally be needed every 18 months. The only other requirement would be maintenance of the groundwater monitoring wells, which is currently an ongoing activity that does not require any additional or special equipment or personnel.

To allow discharge of the treated water to the Missouri River, the effluent from the constructed wetlands at the WSCP and the WSOW would have to meet Missouri NPDES discharge regulations. Monitoring of the treated groundwater prior to its release to the Missouri River would be required to verify compliance with state discharge regulations.

3.5.6.3 Cost

The estimated cost of Alternative 6 is relatively high, even though phytoremediation has been shown to be a low-cost technology for treatment of contaminated sites. The high cost would be due to the required construction of between approximately 330 and 1,000 extraction wells. On the basis of this preconceptual design, which uses preliminary phytoremediation cost data provided in Medina and McCutcheon (1996) and applies cost factors specific to the Weldon Spring site for indirect activities, the capital cost of Alternative 6 is estimated to be between approximately $36 million and $110 million (Appendix F).

Including the annual operating cost of the phytoremediation system and continued groundwater monitoring on an annual basis, the annual O&M cost is estimated to be between approximately $0.8 million and $1.8 million per year (Appendix F). The annual O&M costs would be primarily for groundwater monitoring. Assuming a discount rate of 7% per year, the 30-year present worth of Alternative 6 is estimated to be between approximately $46 million and $130 million (Appendix F).

3.5.7 Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater

Alternative 7 would involve extraction of TCE-contaminated groundwater and ex-situ treatment on-site using adsorption onto GAC, and no further action except monitoring for the other groundwater contaminants. This alternative is described in Section 3.3.2.7.

3.5.7.1 Effectiveness

Alternative 7 would actively remediate only TCE. Alternative 7 would protect human health and the environment by remediating the contaminated groundwater so that when the remediation was complete, the TCE concentration in groundwater at the WSCP and the WSOW would be below the ARAR of 5 µg/L. In addition, TCE migration would be largely halted upon implementation of this alternative, and any potential future contamination by TCE of the aboveground springs would be effectively prevented. Alternative 7 might be expected to attain ARARs for TCE when remediation was completed. Installation has been estimated to take approximately two to three years..

Alternative 7 would reduce the volume of TCE through treatment and would afford long-term protection against further spread in the groundwater system. Alternative 7 would also be protective of human health and the environment over the long term for groundwater contaminants other than TCE. Monitoring and investigative activities by the DOE and DA would enable identification of any potential continued plume migration and any variations in local geochemical conditions (such as Eh to measure metabolic activity, pH, and availability of nutrients/electron acceptors such as oxygen, etc.) that could adversely affect removal of the contaminants from the groundwater by precipitation, biodegradation, and other natural processes. These activities would ensure that remediation goals were being met and that the contaminant distribution in the water-bearing zone was tracked. Response measures, such as land use restriction, would be considered if

data indicate that contamination would result in unacceptable exposure concentrations in the future. Unacceptable impacts to human health and the environment are not expected to occur.

The short-term impacts associated with this alternative are associated with the physical hazards to workers during installation of the extraction wells, construction and operation of the groundwater treatment facilities and operation of the monitoring systems; criteria pollutant emissions during construction; disturbance of soil and its resulting airborne dust emissions; and off-site transport of spent carbon. Appropriate mitigative measures would be enacted during construction and operations to protect the workforce and the public. Exposure to VOCs is possible from duct leaks or venting from the wells. Air monitoring would be used to make sure that the controls are working. Protective equipment and dust suppression methods would be enacted to minimize short-term risks to workers. Precautions would be taken to prevent spills or releases during transportation of GAC canisters for off-site treatment and disposal. More short-term impacts would result from this alternative than from Alternative 8 because of the large number of extraction wells that have to be installed (between 200 and 650 wells).

For Alternative 7 to remain effective over the long term for contaminants other than TCE (which would be remediated under this alternative), careful consideration would have to be given to monitoring, maintenance, and control over a relatively long period (i.e., greater than 100 years). Because this alternative would leave contaminants on-site at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

Alternative 7 would not satisfy the statutory preference for treatment as a principal element of remediation for contaminants other than TCE, and there would be no reduction in toxicity, mobility, or volume of the contaminated groundwater through treatment for contaminants other than TCE. Contamination would remain relatively high in the short term; however, the concentration of groundwater contaminants at the WSCP and the WSOW is expected to decrease with time because of the removal of the original sources of the contamination and the natural processes that occur, including dilution by infiltration and biodegradation.

3.5.7.2 Implementability

A number of implementability concerns would be posed by Alternative 7. The potential concerns with groundwater monitoring and groundwater extraction and treatment using GAC would be similar to those discussed for Alternatives 2 and 4, respectively.

A major implementability issue would concern the extraction of TCE-contaminated groundwater. The proposed groundwater extraction system might not be effective for aquifer restoration to ARARs for TCE.

No special equipment would be required to implement Alternative 7. It might, however, become necessary to conduct detailed studies to determine whether the performance of the proposed groundwater extraction well network would achieve acceptably low concentrations in the groundwater. Resources required for maintenance and monitoring should be readily available.

A major implementability concern for Alternative 7 would be the possibility of dewatering the shallow aquifer. Enhancing the recovery of contaminants from the shallow aquifer if dewatering occurs may require pulsed pumping. In pulsed pumping, some or all extraction pumps are turned off and then back on for specified periods of time. Although not widely used in remedies to date, pulsed pumping can recover contaminants located in the portions of an aquifer than have been dewatered, eliminate flow stagnation areas, and allow sorbed contaminants to partition into groundwater. Application of pulsed pumping (or other measures such as adjusting the rate of extraction from some or all wells) may affect the time frame estimated to achieve a maximum TCE groundwater concentration of 5 μg/L.

To allow discharge of the treated water to the Missouri River, the groundwater treatment facility would have to meet the substantive requirements and standards of Missouri NPDES regulations. Monitoring of the treated groundwater prior to its release to the Missouri River would be required to ensure compliance with state discharge regulations.

3.5.7.3 Cost

The estimated cost of Alternative 7 is much higher than that of Alternative 8. On the basis of the preconceptual design and application of cost factors for indirect activities, the capital cost of Alternative 7 is estimated to range between $9 million and $25 million, depending on the number

of extraction wells required (i.e., 200 to 650 wells). The capital cost would be primarily for installation of the 200 to 650 extraction wells.

The annual O&M cost is estimated to range between $1 million and $2 million per year. The annual O&M costs would be primarily for groundwater extraction and treatment. Assuming a discount rate of 7% per year, the 30-year present worth of Alternative 7 is estimated to range from $23 million to $53 million, much greater than that for Alternative 8.

3.5.8 Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping

Alternative 8 would consist of in-situ treatment of groundwater contaminated with TCE using in-well vapor stripping and no further action except monitoring for other groundwater contaminants. This alternative is described in Section 3.3.2.8.

3.5.8.1 Effectiveness

Similar to Alternative 7, Alternative 8 would actively remediate only TCE. Alternative 8 would protect human health and the environment by remediating the contaminated groundwater so that when remediation is complete, the TCE concentration in the groundwater within the WSCP would be below the ARAR of 5.0 µg/L. In addition, TCE migration would be largely halted upon implementation of this alternative, and any potential future large-scale contamination of the aboveground springs by TCE would be effectively prevented. Alternative 8 might be expected to attain ARARs for TCE when remediation was completed. Installation and operations have been estimated to take approximately two to three years.

Alternative 8 would reduce the volume of TCE through treatment and affords long-term protection against potential widespread groundwater contamination. Alternative 8 would also be protective of human health and the environment over the long term for groundwater contaminants other than TCE. Monitoring and investigative activities by the DOE and DA would enable identification of any potential continued plume migration and any variations in local geochemical conditions (such as Eh to measure metabolic activity, pH, and availability of nutrients/electron acceptors such as oxygen, etc.) that could adversely affect removal of the contaminants from the groundwater by precipitation, biodegradation, and other natural processes. These activities would ensure that remediation goals were being met, and that the contaminant distribution in the water-

bearing zone was tracked. Active response measures would be considered if future migration of residual contamination would result in unacceptable exposure concentrations at potential existing or foreseeable receptors. Unacceptable impacts to human health and the environment would not be expected to occur.

The short-term impacts associated with this alternative are associated with the physical hazards to workers during construction of the vapor stripping wells and operation of the in-well vapor stripping remediation system, minor criteria pollutant emissions during construction, and the disturbance of soil and its resulting airborne dust emissions. Appropriate mitigative measures would be enacted during construction and operations to protect the workforce and the public. Exposure to TCE from duct leaks or venting from the wells is possible. Air monitoring would be used to make sure that the controls are working. Protective equipment and dust suppression methods would be enacted to minimize short-term risks to workers. Precautions would be taken to prevent spills or releases during transportation of GAC canisters for off-site treatment and disposal. More short-term impacts would result from this alternative than from Alternative 7, because of the off-site transport of spent carbon for disposal purposes.

For Alternative 8 to remain effective over the long term for contaminants other than TCE (which would be remediated under this alternative), careful consideration would have to be given to monitoring, maintenance, and control over a relatively long period (i.e., greater than 100 years). Because this alternative would leave contaminants on-site at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

Alternative 8 would not satisfy the statutory preference for treatment as a principal element of remediation, and there would be no reduction in toxicity, mobility, or volume of the contaminated groundwater through treatment for contaminants other than TCE. Residual contamination would remain high in the short term; however, the concentrations of contaminants at the WSCP and the WSOW have decreased with time because of the removal of the original source of the contamination, dilution from infiltration from rainwater and runoff, and biodegradation.

3.5.8.2 Implementability

A number of implementability concerns would be posed by Alternative 8. The potential concerns with groundwater monitoring and adsorption using GAC would be similar to those discussed for Alternatives 2 and 4, respectively.

One potential concern for Alternative 8 is the application of the in-well vapor stripping technology at the WSCP and the WSOW. In-well stripping has been used in a variety of soil types from silty clay to gravel. Since reinfiltration of stripped water is integral to the process, the soil should be low in clay content and exceed a hydraulic conductivity of 1×10^{-5} cm/s (0.03 ft/d). Because the in-well vapor stripping system would have to be installed into the shallow (consolidated) bedrock aquifer with hydraulic conductivities two to three orders of magnitude lower than the minimum hydraulic conductivity of 1×10^{-5} cm/s (0.03 ft/d) in some locations, the application of this remediation technology would appear to require field testing and treatability studies under site-specific conditions.

Correct placement of the in-well vapor stripping remediation system would require accurate predictions of TCE migration. Because of the lack of historical data and an unknown source area, the final detailed design might have to be more conservative than that presented in Section 3.3.2.8 to compensate for these uncertainties.

Another potential concern is that the circulation pattern of the in-well stripping technology cannot be assured at some sites and could potentially lead to loss of hydraulic control of the reinfiltrating water (Cichon et al. 1997). If the vapor stripping wells are not properly designed or constructed, the TCE-contaminated zone may spread beyond the radius of influence of the vapor stripping wells.

On the basis of an assumed stripping efficiency of 90%, between two to three recirculations of TCE-contaminated groundwater through the in-situ vapor stripping process would be necessary to achieve the ARAR of 5 µg/L. Because of the heterogeneity of the TCE-contaminated zone in terms of aquifer thickness and hydraulic conductivity (both horizontal and vertical), it is not known whether the required number of recirculations would be achieved.

In-well stripping removes excess CO_2 from the groundwater and equilibrates the groundwater with atmospheric CO_2 levels. As the CO_2 is stripped from the groundwater, the pH

rises. Chemical precipitates may form during air stripping and may clog the well screens, thus limiting groundwater circulation. High levels of dissolved iron and/or manganese and high alkalinity can also cause problems [HazTECH 1997], and these factors appear to exist within the shallow aquifer containing the TCE contamination. Managing the chemical changes in the groundwater, soil, and aquifer (such as chemical precipitation or oxidation) that may accompany use of this system [PNNL 1994] could potentially be challenging.

No special equipment would be required to implement Alternative 8. The method itself involves no moving parts beneath the ground surface; however, careful packer and well designs would be required to successfully divert the groundwater from the well back into the unsaturated zone and to the water table. Most of the equipment used in this technology is available off-the-shelf and has been proven reliable. The system is designed to run continuously with only routine maintenance. One to two persons would be required to maintain and monitor the in-well vapor stripping system. However, the expertise needed to use and monitor the in-well vapor stripping technology is limited to three suppliers in the private sector (Miller and Roote 1997).

The application of in-well vapor stripping for the remediation of TCE in bedrock aquifers is in the developmental phase, and numerous aspects of the in-well vapor stripping process, as considered for Alternative 8, have not been proven (e.g., its application in a consolidated aquifer at hydraulic conductivities lower than 1×10^{-5} cm/s [0.03 ft/d]). The technical feasibility of this aspect of Alternative 8 appears uncertain.

Groundwater monitoring would be required to track the progress and effectiveness of the groundwater remediation. Monitoring at various depths may be necessary to show that the appropriate recirculation path has been established. Resources required for maintenance of the groundwater monitoring wells should be readily available. No new permits or license for on-site activities would be required to implement Alternative 8.

3.5.8.3 Cost

The estimated cost of Alternative 8 is slightly higher than that of Alternative 7. On the basis of the preconceptual design and application of cost factors for indirect activities, the capital cost of Alternative 8 is estimated to range between $1 million and $3 million (Appendix F). The capital cost would be primarily for installation of the vapor stripping and monitoring wells.

The annual O&M cost is estimated to be approximately $0.5 million per year (Appendix F). The annual O&M costs would be primarily for groundwater monitoring. Assuming a discount rate of 7% per year, the 30-year present worth of Alternative 8 is estimated to range between $5 million and $7 million (Appendix F), much lower than that of Alternative 7.

3.6 SCREENING SUMMARY AND IDENTIFICATION OF FINAL ALTERNATIVES

The results of the screening analysis for the preliminary alternatives are presented in Table 3.2. Each alternative was evaluated against the three criteria defined in 40 CFR Part 300: effectiveness, implementability, and cost. On the basis of the screening process, the following alternatives were excluded from further consideration:

- Alternative 3: Natural Attenuation;
- Alternative 4: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds using Granular Activated Carbon;
- Alternative 5: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using Ultraviolet Oxidation;
- Alternative 6: Groundwater Removal, On-Site Treatment Using Phyto-remediation;
- Alternative 7: Ex-Situ Treatment of TCE-Contaminated Groundwater; and
- Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping.

Alternative 3 was not retained for further consideration because of implementability concerns associated with demonstrating natural attenuation, including development and measurement of necessary biodegradation rates for contaminants other than DNT and three-dimensional contaminant transport and flow modeling of the shallow aquifer where two regimes of groundwater flow (diffuse flow and high-velocity turbulent flow) are postulated to exist. Alternative 3 was also rejected because it does not provide greater protection of human health and the environment compared with Alternative 2.

TABLE 3.2 Screening of Preliminary Alternatives

Alternative	Effectiveness	Implementability	Cost
Alternative 1: No Action	Would provide protection of human health and the environment only as the result of natural processes. Would allow for the possible continued migration of the contaminated groundwater and further degradation of the groundwater. No reduction in toxicity, mobility, or volume of the contaminated groundwater would occur because no treatment would be carried out.	No implementability concerns because no action would be taken. No technologies or management strategies would be implemented, nor would any permits, licenses, or approvals associated with undertaking a remedial action be needed.	No net present worth, capital, or annual O&M costs because no activities would be undertaken.
Alternative 2: Monitoring with No Active Remediation	Same as Alternative 1. Monitoring would allow for collecting data to verify that beneficial impacts are occurring from source removal and to verify expectations that contaminants would decrease over time. Potential for minor short-term impacts to workers (mainly from monitoring).	Few implementability concerns because of the limited actions taken. The site could easily monitor contaminant migration. Proposed monitoring would provide notice of failure before significant exposure occurred; consideration of additional actions prior to significant exposure would be easy. No special equipment or specialists would be needed, and resources required for maintenance of monitoring wells would be readily available.	Low capital expenditures, annual costs (associated with monitoring activities), and present-worth costs.
Alternative 3: Natural Attenuation	Same as Alternative 2. Potential for minor short-term impacts to workers (mainly from monitoring and subsurface data collection).	Implementability concerns associated with development and measurement of necessary biodegradation rates, and the need for three-dimensional contaminant transport and flow modeling.	Low capital expenditures and present-worth costs. Moderate annual costs (associated with monitoring activities and investigative activities).

TABLE 3.2 (Cont.)

Alternative	Effectiveness	Implementability	Cost
Alternative 4: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using Granular Activated Carbon	Would protect human health and the environment by remediating contaminated groundwater. Might be expected to attain all PRGs when remediation was complete. Would reduce the volume of contaminants through treatment and would afford long-term protection. No long-term action would be required after remediation was complete. Some potential for short-term impacts associated with transport of groundwater treatment residuals for on-site storage and disposal (prior to closure of the on-site disposal cell), potential transport of groundwater treatment residuals for off-site disposal, physical hazards to workers during construction and operations, criteria pollutant emissions during construction, and disturbance of soil and resulting airborne dust emissions. Time to achieve remediation goals would be at least about 100 years.	Implementability concerns associated with potential failure of groundwater extraction to remove contaminants to acceptably low concentrations and the proposed location of extraction wells. No special equipment or specialists would be required for implementation. Resources required for maintenance and monitoring should be readily available. Implementability concerns about continued replacement of groundwater treatment facilities and disposal of contaminated wastes.	Moderate-to-high capital expenditures (associated with extraction well installation and construction of groundwater treatment facilities). Moderate annual costs (associated with operation of extraction wells and treatment facilities). High 30-year present-worth costs.
Alternative 5: Groundwater Removal, On-Site Treatment of TCE and Nitroaromatic Compounds Using Ultraviolet Oxidation	Same as Alternative 4.	Implementability would be similar to Alternative 4. Special equipment, the ultraviolet oxidation unit, would be required.	Moderate to high capital expenditures (associated with extraction well installation and construction of groundwater treatment facilities). Moderate annual costs (associated with operation of extraction wells and treatment facilities). High 30-year present-worth costs.
Alternative 6: Groundwater Removal, On-Site Treatment Using Phytoremediation	Same as Alternative 4, except that the time to achieve remediation goals would be at least 130 years.	Implementability would be similar to Alternative 4, except that phytoremediation is in the developmental scale. No special equipment or personnel would be required.	Moderate to high capital expenditures (associated with extraction well installation). Low to moderate annual costs (associated with monitoring). Moderate to high 30-year present-worth costs.

TABLE 3.2 (Cont.)

Alternative	Effectiveness	Implementability	Cost
Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater	Would protect human health and the environment by remediating TCE-contaminated groundwater. Might be expected to attain the PRG for TCE when remediation was complete. Would reduce the volume of TCE contamination through treatment and would afford long-term protection. Monitoring would allow consideration of active response measures for migration of other contaminants in the future. Some potential for short-term impacts associated with physical hazards to workers during construction and operations of pump-and-treat system, and minor short-term impacts to workers from monitoring. Time to achieve remediation goals on the order of at least 100 to 500 years for contaminants other than TCE.	Implementability concerns associated with potential failure of groundwater extraction to remove contaminants to acceptably low concentrations and the proposed location of extraction wells. No special equipment or specialists would be required for implementation. Resources required for maintenance and monitoring should be readily available. Implementability concerns about continued replacement of groundwater treatment facilities and disposal of contaminated wastes.	High capital expenditures. Low-to-moderate annual costs (associated with activities and groundwater extraction and treatment). Moderate 30-year present-worth costs.
Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping	Same as Alternative 7.	Implementability concerns associated with developmental scale of in-well vapor stripping process. No special equipment or specialists would be required. Resources required for maintenance of monitoring wells should be readily available. The site could easily monitor contaminant migration. Proposed monitoring would provide notice of failure before significant exposure occurred; consideration of additional actions prior to significant exposure would be relatively easy.	Low to moderate capital expenditures. Low annual costs (associated with monitoring). Low 30-year present-worth costs.

Alternatives 4 and 5 were not retained for further consideration because the preliminary simulation results indicate that restoration time frames of about 100 years would generally be necessary to restore the groundwater system using the extraction technology. These projected remediation time frames for removal of nitroaromatics and nitrates, which would be controlled by the low extraction rate, would require groundwater treatment capacity to extend considerably beyond the 30-year design life of any proposed groundwater treatment facility. Replacement facilities would be required for many years into the future to satisfy long-term removal and treatment needs.

Other major implementation issues for rejection of Alternatives 4 and 5 are associated with the high number of extraction wells required (between 330 and 1,000 total), with the resulting generation of substantial amounts of wastewater that must be treated, the general inapplicability of conventional extraction to fractured rock sites, and the general inability of this technique to comply with drinking water standards (due to mass transfer limitations or the potential presence of DNAPLs). Pump-and-treat systems are considered a relatively poor choice for contaminants that adsorb to subsurface materials or that have low solubilities. These implementability issues raise uncertainties regarding the technical feasibility of Alternatives 4 and 5.

Alternative 6 was not retained for further consideration because of the above-cited implementability issues associated with conventional extraction and because the technology is not well established and might be rejected for technical reasons during the remedial design phase.

Alternatives 7 and 8 were retained for further consideration. A detailed analysis of these two alternatives is warranted in order to provide the information that would allow for the consideration of an active remediation option to address TCE, if any. TCE has been reported at relatively higher concentrations than the other contaminants, and it is also located in a somewhat definable continuous plume. TCE is the primary contributor to estimated potential human health risk as presented in the BRA (DOE and DA 1998a). Therefore, any reduction of TCE contamination could result in a relatively large decrease in the estimated potential risk results.

On the basis of the screening process, the following alternatives were retained for detailed evaluation:

- Alternative 1: No Action;
- Alternative 2: Monitoring with No Active Remediation;

- Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater; and
- Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping.

These alternatives are discussed further in Chapters 4 and 5.

4 DETAILED ANALYSIS OF FINAL ALTERNATIVES

Two of the eight remedial action alternatives considered for the GWOUs at the WSCP and the WSOW were retained through the screening process presented in Chapter 3:

- Alternative 1: No Action; and
- Alternative 2: Monitoring with No Active Remediation.

These alternatives are described further in Sections 4.1 and 4.2. Engineering information and identification of any required equipment that would be representative of a final remedial design are provided for the purpose of comparing the feasibility of the alternatives and assessing potential impacts on human health and the environment. Actual equipment requirements and engineering procedures would be defined in the ROD or subsequent remedial design/remedial action reports, as appropriate.

A detailed analysis of these two final alternatives consisted of an assessment of each alternative relative to the following nine evaluation criteria as specified in the NCP:

1. ***Overall protection of human health and the environment*** — addresses whether each alternative provides adequate protection of human health and the environment. Evaluation focuses on a specific alternative's ability to achieve adequate protection and describes how site risks posed by each pathway are eliminated, reduced, or controlled through natural processes, treatment, engineering, or institutional controls. This evaluation also allows for consideration of any unacceptable short-term impacts associated with each alternative. Because of its broad scope, this criterion also reflects the focus of criteria 2 through 5.

2. ***Compliance with ARARs*** — addresses whether all applicable or relevant and appropriate state and federal laws and regulations are met. Evaluation focuses on whether each alternative will meet federal and state ARARs or if there is justification for an ARAR waiver. Various ARARs and the waiver conditions are identified in Appendix A; the key requirements for each alternative are discussed.

3. ***Long-term effectiveness and permanence*** — addresses the risk remaining at the operable unit after remediation goals have been met. Evaluation focuses upon the ability of an alternative to maintain reliable protection of human health and the environment over time, once these goals have been met.

4. ***Reduction of toxicity, mobility, and volume*** — addresses the statutory preference for selecting alternatives that permanently and significantly reduce the toxicity, mobility, or volume of hazardous substances at a site. Evaluation focuses upon the extent to which this is achieved by each alternative.

5. ***Short-term effectiveness*** — addresses the potential impacts to workers, the general public, and the environment during implementation of each alternative.

6. ***Implementability*** — addresses technical and administrative feasibility, including the availability and reliability of resources or materials required during implementation, and the need to coordinate with other agencies.

7. ***Cost*** — addresses both capital costs and annual O&M costs, as well as the combined net present worth of each alternative.

8. ***State acceptance*** — addresses the statutory requirements for substantial and meaningful state involvement. Evaluation of this criterion will be addressed in the responsiveness summary and ROD that will be prepared following the public comment period.

9. ***Community acceptance*** — assesses the community's apparent preference for, or concerns about, the alternatives being considered. Evaluation of this criterion will be addressed in the responsiveness summary and ROD that will be prepared following the public comment period.

The effectiveness, implementability, and cost of the two alternatives retained for detailed analysis are summarized in Table 3.1. The two alternatives that were retained through the screening process were evaluated on the basis of criteria 1 through 7 relative to potential health and environmental impacts. The results of this comprehensive analysis are presented in Sections 4.1 and 4.2.

4.1 ALTERNATIVE 1: NO ACTION

The no action alternative provides a baseline against which other alternatives can be evaluated. Under this alternative, the WSCP and the WSOW would remain "as is." No containment, removal, treatment, or other mitigative actions would be implemented. However, it was assumed that the source-control measures listed in Section 3.1 would have been completed. The no action alternative does not include groundwater monitoring by the DOE and DA or any additional active or passive institutional controls that could reduce any potential for human exposure (e.g., physical barriers, deed restrictions). Under Alternative 1, it was assumed that all existing activities, including groundwater monitoring by the DOE and DA, would be discontinued.

4.1.1 Overall Protection of Human Health and the Environment

The no action alternative might be adequately protective of human health and the environment over the long term. Under current conditions, the contaminated groundwater at the WSCP and the WSOW poses no imminent risk to human health or the environment. The groundwater is not accessible and is not used at the sites. The likely future land use is considered to be similar to current land use. Groundwater contaminant levels are also expected to decrease with time due to source removals and naturally occurring processes that would further attenuate contaminant concentrations.

4.1.2 Compliance with Potential ARARs

Potential regulatory requirements that might be applicable or relevant and appropriate to the final remedial action alternatives are identified and evaluated in Appendix A. With no action, the levels of nitrates in groundwater, primarily near the raffinate pits at the WSCP, would exceed the relevant and appropriate MCL of 10 mg/L (40 CFR 141.62) or 20 mg/L under the variance available to noncommunity drinking water systems if the water is not available to children under 6 months of age and if certain other conditions are met. No ARARs exist for the nitroaromatic compounds. Several wells at the WSCP (mostly completed in the weathered unit of the shallow aquifer system) also contain concentrations of TCE that exceed the MCL of 5 µg/L. The concentration of contaminants in groundwater at the WSCP and the WSOW will continue to decrease with time due to removal of the sources of contamination and naturally occurring processes

(e.g., biodegradation of the organic contaminants and dilution through infiltration of rainwater and storm-water runoff).

4.1.3 Long-Term Effectiveness and Permanence

Under current conditions and land use, groundwater at the WSCP and the WSOW poses no imminent risk to human health or the environment. Although groundwater contaminant concentrations would not be measured in the future, it is expected that no potential impacts would occur because of the likely future land use of the WSCP and the WSOW.

4.1.3.1 Protection of Workers

No activities are associated with the no action alternative, so workers would not be exposed to contaminants. Thus, there would be no unacceptable health risks to workers associated with this alternative.

4.1.3.2 Protection of the Public

Potential impacts to members of the general public are summarized in Section 1.3. Estimated current risks are assumed to be representative of likely future risks because land uses and risk scenarios can be assumed to be similar. On the basis of these risk results, unacceptable risks to members of the general public are not likely to occur under the no action alternative. Contaminant concentrations are expected to decrease with time due to source removals and natural processes that occur at these sites. However, in the event that access and use of the contaminated groundwater do occur, exposure to current concentrations of the contaminants of concern could result in unacceptable risks to human health.

4.1.3.3 Environmental Protection (Water Quality and Hydrology)

Contaminant concentrations in groundwater at the WSCP and the WSOW should decrease with time, primarily because of source removals (see Section 3.3.1) and natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials. Infiltration from rainwater and runoff would also dilute the contaminant concentrations in the groundwater. The existing contamination in groundwater would remain and could further migrate beyond the

boundaries of the operable units. On the basis of fate and transport modeling results obtained with the analytical solute transport model BIOSCREEN (EPA 1996a), natural processes will likely reduce TCE concentrations below remediation goals at potential exposure points like the area surface springs (Appendix E). This result is primarily due to dilution/dispersion and biodegradation assumptions used in the calculations (the recommended first-order biodegradation rate option was utilized). Over the long term, groundwater contamination would be expected to decrease gradually. Future unacceptable impacts to surface springs located at the WSCP and the WSOW are therefore not expected.

4.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment

Reduction of toxicity, mobility, or volume through treatment is not applicable to Alternative 1 because the contaminated groundwater would not be treated under this alternative.

4.1.5 Short-Term Effectiveness

No short-term impacts would occur to human health or the environment because no remedial action would be conducted. The lack of extensive construction activities would negatively impact the sites less than a more rigorous remedial effort.

4.1.6 Implementability

No concerns regarding implementability are associated with Alternative 1 because no action would be taken nor would any future activities be considered. No technologies or management strategies would be implemented, nor would any permits, license, or approvals associated with undertaking a remedial action be needed.

4.1.7 Cost

No net present worth, capital, or annual O&M costs are associated with the no action alternative because no activities would be undertaken.

4.2 ALTERNATIVE 2: MONITORING WITH NO ACTIVE REMEDIATION

The activities associated with Alternative 2 include the following:

- Source-control response actions implemented per RODs for the WSCP and WSOW that would prevent further release of contaminants to groundwater;
- Performance monitoring of groundwater to verify that future contaminant concentrations would not result in unacceptable risks to human health;
- Institutional controls to ensure that contaminated groundwater was not used before protective concentrations were attained; and
- Contingency measures in the event that natural processes do not result in acceptable off-site concentrations and exposure.

The concentrations of contaminants in groundwater at the WSCP and the WSOW are expected to decrease with time. This decrease could be due to a number of environmental processes affecting contaminant fate and migration, including (1) source removals, (2) transformation (i.e., hydrolysis, photolysis, oxidation/reduction, chemical precipitation, radioactive decay, and biodegradation), (3) transfer (i.e., adsorption/desorption and dissolution), and (4) dilution through infiltration of rainwater and runoff (DOE and DA 1997b). Further evaluation through long-term monitoring and associated activities would determine whether these processes had resulted in decreased contamination, thereby minimizing potential risks to human health and the environment at these operable units.

Groundwater monitoring would be conducted using the existing well network, as appropriate. This network could be expanded or reduced, depending on the results of future efforts to optimize the network for long-term monitoring. As a conservative approach, the evaluation of Alternative 2 for this assessment assumed the installation and operation of additional monitoring wells equivalent to approximately 10% of the number of existing wells (i.e., about 15 additional wells). The exact monitoring network and details regarding frequency of sampling and parameters analyzed will be identified in the ROD or subsequent remedial design/remedial action reports for these operable units. The current groundwater monitoring program conducted by the DOE and DA consists of 73 wells at the WSCP and 79 wells at the WSOW, respectively. (The current [July 1997] monitoring program conducted by the DA sampled 49 wells and 6 springs.) Of these wells,

10 monitor groundwater in the soil overburden. The remaining wells are screened in the bedrock system (Burlington/Keokuk, Fern Glen/Chouteau, Kimmswick, Joachim/St. Peter).

The monitoring program would continue for a reasonable period of time and would be evaluated during the review of the effectiveness of the remedy at least every five years or until remediation goals identified in the ROD were achieved. Standard operating procedures used for the current monitoring activities would be expected to be adopted for the long-term monitoring effort. These monitoring efforts would include such activities as water-level measurements and the collection of quality assurance/quality control samples during each sampling event.

The monitoring frequency for the wells is expected to be location-specific, depending on the level of contamination encountered. For example, wells with low concentrations of contaminants that were constant or decreasing over time would be sampled less frequently than wells with contaminant concentrations much greater than the PRGs. For this analysis, it was assumed that the frequency of sampling would be annual (once per year). Details of the final monitoring scheme will be presented in subsequent reports prepared for these operable units, as appropriate.

Periodic maintenance of the groundwater monitoring wells and purge pumping equipment would be expected to extend the life of the equipment. Monitoring wells would be evaluated with regard to performance and condition and integrity of various well components such as concrete pads, posts, and protective casings. Periodic inspections to determine the need for maintenance would be guided by the collection and analysis of representative groundwater samples. After the completion of long-term monitoring activities, the monitoring wells would be managed in accordance with on-site procedures (e.g., plugged and abandoned).

Because contaminants would remain on-site above health-based levels, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment. If monitoring showed that the contaminated area and level of contaminants in the groundwater had decreased significantly during the prior five-year period, the number of wells sampled and the sampling frequency might be reduced. Wells that duplicated information, provided unreliable information (e.g., wells that were dry part of the year), or sampled groundwater concentrations below the ARARs for all contaminants might be considered

for elimination. The number of monitoring wells and sampling frequency would be determined in collaboration with the regulators.

Other limitations or controls on groundwater use at the GWOUs include St. Charles County zoning requirements and restrictions by the Missouri Department of Conservation on land not currently under federal ownership (see Section 1.1.2.5). Zoning of properties other than the WSCP and the WSTA at the WSOW might become relevant under some future period.

Continued federal ownership of the WSTA at the WSOW and the area containing the on-site disposal cell at the WSCP appears certain and would involve continued control by the federal government with the intent to restrict site development activities through the rights of ownership. On-property development activities, such as agricultural or residential usage, could be restricted or eliminated.

4.2.1 Overall Protection of Human Health and the Environment

Alternative 2 might be adequately protective of human health and the environment over the long term. Potential migration of the contamination toward the surface springs would be monitored. The data collected would be used to identify any potential for continued migration and any variations in local geochemical conditions (e.g., Eh to measure metabolic activity, pH, and availability of nutrients/electron acceptors such as oxygen). These variations could adversely affect the removal of contaminants from the groundwater as a result of natural processes such as microbial biodegradation, photolysis, chemical precipitation, radioactive decay, sorption, and hydrolysis. This monitoring program would be used to measure the attainment of remediation goals, that is, to determine whether groundwater contaminant concentrations are equal to or less than the PRGs. Restoration of the water-bearing zone within the operable units would be provided by existing natural processes that would be expected to attenuate contaminant concentrations. Dilution of the contaminated groundwater with uncontaminated groundwater drawn through infiltration of rainwater and runoff could also result in decreased concentrations.

4.2.2 Compliance with Potential ARARs

Compliance with potential ARARs for Alternative 2 would be the same as for Alternative 1 (Section 4.1.2).

4.2.3 Long-Term Effectiveness and Permanence

Under current land use conditions, groundwater is not used and, therefore, poses no imminent risk to human health or the environment. Deed restrictions could be used to ensure that no new wells would be installed in the area of the contaminated groundwater, but these restrictions could be difficult to enforce without the application of additional controls (e.g., access restrictions). Additional protection for off-site residents is currently provided by quarterly sampling of off-site wells by the Missouri Department of Health. Continued federal ownership would eliminate any potential risks associated with on-property groundwater. Monitoring and maintenance activities would be carried out by the DOE and DA at these operable units for a reasonable period. Protection of human health and the environment in the extended future would be provided because monitoring activities by the DOE and DA would continue and allow consideration of contingency measures to protect human health and the environment. However, unacceptable impacts to human health and the environment would not be expected to occur.

4.2.3.1 Protection of Workers

Long-term monitoring and maintenance activities under Alternative 2 would be carried out for a reasonable period of time and would be evaluated during review of the effectiveness of the remedy at least every five years, or until remediation goals identified in the ROD were achieved. Workers would be present on-site periodically to perform these monitoring and maintenance activities. The potential impact on sampling personnel from exposure to contaminants would be low.

Monitoring activities over a 30-year period are estimated to result in approximately seven cases of occupational injury and no occupational fatalities; these estimates are based on industry-specific statistics from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995). Alternative 2 would therefore pose low long-term risks to workers.

4.2.3.2 Protection of the Public

Similar to the no action alternative, unacceptable risks to the general public would not be expected to occur under Alternative 2. Even if contaminant concentrations remained as they are now, the pathway for exposure to groundwater contamination is not complete (i.e., current and likely

future land uses are considered to be recreational). However, with monitoring, information on future concentrations of contaminants in groundwater would be available to confirm this expectation.

4.2.3.3 Environmental Protection (Water Quality and Hydrology)

Water quality and hydrology would be the same for Alternative 2 as for Alternative 1.

4.2.4 Reduction of Toxicity, Mobility, and Volume through Treatment

Reduction of toxicity, mobility, and volume through treatment is not applicable to Alternative 2 because the contaminated groundwater would not be treated under this alternative.

4.2.5 Short-Term Effectiveness

Construction activities are estimated to result in less than one case of occupational injury and no occupational fatalities. This estimate is based on industry-specific statistics from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995).

Some short-term impacts on recreational use of the surrounding wildlife areas might occur as a result of noise, exhaust fumes, and dust associated with any construction of new monitoring wells. Impacts to biological resources would be mitigated by avoiding unnecessary damage to vegetation, wildlife, and soil through controlling traffic and minimizing the areas of disturbance.

During construction of the 15 proposed monitoring wells, the amount of criteria pollutants emitted as a result of equipment operations and transportation (by car) of the construction personnel to the operable unit would be low (e.g., less than 470 kg [1,100 lb] of CO emitted during the entire construction period [Appendix G]) and as such, would not contribute to any off-site health impacts. Assuming a total of 167 (152 existing, 15 assumed new) DOE and DA monitoring wells, an annual sampling frequency, a mobilization distance of 8 km (5 mi), and (conservatively) only one well sampled per trip, the annual emission rate of criteria pollutants from worker vehicles would be low (e.g., less than 22 kg [50 lb] per year of carbon monoxide emitted [Appendix G]) and would not contribute to any off-site health impacts. These temporary impacts would be limited to the immediate vicinity of the operable unit, and mitigative measures would be applied to ensure minimal impacts to off-site areas.

4.2.6 Implementability

Few implementability concerns would be posed by Alternative 2 because of the limited actions taken. Site operations would continue to use readily available resources for monitoring and maintaining institutional controls. Construction of any new monitoring wells would simply require mobilization of a drilling rig for installation. Minimal administrative complexities, including permit applications, would be associated with monitoring well installation.

Groundwater monitoring could be readily implemented. Numerous wells currently exist at these operable units; additional wells could be easily installed and monitored. Monitoring of potential off-site contaminant migration would be relatively easy to implement. The results from sampling of the existing monitoring well network would be used to identify the potential for any unacceptable exposure before it occurred.

Implementation of institutional controls would require only administrative effort and legal enforcement. Continued federal ownership could be readily implemented because it represents continuation of the existing situation.

The administrative feasibility of Alternative 2 would be relatively straightforward. Remediation activities at the WSCP and the WSOW are coordinated with the State of Missouri and EPA Region VII. That coordination would continue during the implementation of Alternative 2, and no additional coordination would be required with any other agencies beyond that already occurring. No permits or licenses would be required for on-site activities.

4.2.7 Cost

Costs for Alternative 2 would be associated with continuing the existing environmental monitoring program, constructing and operating possible new monitoring wells, and conducting a performance review at least every five years. Feasibility-level cost estimates were prepared using standard cost-estimating sources. The proposed monitoring wells were assumed to be constructed of stainless steel for long-term effectiveness. It was conservatively assumed in this analysis that the new wells would be purged and sampled with dedicated pumps.

The costs for individual construction activities were taken from the latest version of the *Unit Price Book* developed by the U.S. Army Corps of Engineers (1989) and other sources (see

Appendix F). A cost differential was included to account for differences in material and labor costs in the Weldon Spring area compared with the generic *Unit Price Book* costs. The workforce estimates for various support activities (e.g., construction and health and safety) were derived by a parametric approach based upon similar levels of construction activities for related construction projects. Other costs — such as those for small tools, indirect costs, and bond and insurance costs — were estimated on the basis of various percentages of other costs. Present worth was calculated from procedures identified in EPA guidance and using a 7% discount rate. Long-term maintenance costs were based on a 30-year period and include annual sampling and analytical costs.

Estimated total and present-worth costs for Alternative 2 are given in Table 4.1. Costs are estimated to be about $0.34 million. The present-worth cost would increase from $4.8 million for a 30-year period to $5.5 million for a 100-year period.

The costs associated with potential future actions, in the event that potential migration of residual contamination does result in unacceptable exposure concentrations, were not quantified because the uncertainty associated with these future activities precludes accurate assessment of these costs.

TABLE 4.1 Cost Estimate for Alternative 2

Activity	Estimated Cost ($ million)
Monitoring well construction[a]	0.31
Groundwater monitoring[b]	10.8
Total[b]	11.1
Present worth [b]	4.8

[a] Based upon construction of 15 new monitoring wells

[b] Estimated upper-bound cost for a 30-year period, assuming annual sampling frequency for the existing network of monitoring wells. Any reduction in duration of monitoring, sampling frequency, or number of wells sampled would result in a proportional reduction in cost.

4.3 ALTERNATIVE 7: REMOVAL AND EX-SITU TREATMENT OF TCE-CONTAMINATED GROUNDWATER

The activities associated with Alternative 7 include the following:

- Extraction and ex-situ treatment of the groundwater primarily at the WSCP near the raffinate pits area contaminated with TCE to achieve a maximum TCE groundwater concentration of 5 µg/L;
- Source-control response actions implemented per RODs for the WSCP and the WSOW that would prevent further release of contaminants to groundwater;
- Performance monitoring of groundwater to verify that future contaminant concentrations would not result in unacceptable risks to human health;
- Institutional controls to ensure that contaminated groundwater was not used before protective concentrations were attained; and
- Contingency measures in the event that natural processes did not result in acceptable off-site concentrations and exposure.

The objectives and design of Alternative 7 are similar to those for Alternative 3, except that only groundwater exceeding PRGs for TCE would be removed and treated by this alternative. Groundwater exceeding a TCE concentration of 5 µg/L would be removed by using conventional extraction wells, pumped to and treated in an aboveground treatment system consisting of a sequence of physical and chemical unit operations, and released to a permitted discharge point. An approach identical to that described in Alternative 2 would be applied to manage other contaminants in the groundwater. This alternative provides for active remediation of TCE only.

Approximately 200 to 650 vertical extraction wells at the WSCP and the WSOW (see Appendix C) were estimated to be required to achieve a reasonable extraction rate and to provide wide enough coverage so as not to allow any bypass of the TCE. The wells would be between 16 m (50 ft) and 30 m (100 ft) deep, have a screened length of about 10 m (30 ft), and be approximately 15-cm (6-in.) in diameter. However, additional field investigation of the shallow aquifer characteristics would be necessary for more accurate estimation of the number of extraction wells

wells necessary, the optimal location for placement of these extraction wells, and a better determination of groundwater extraction rates.

A single groundwater treatment facility was assumed to be constructed. with a treatment capacity ranging between 4 to 12 L/s (60 to 195 gpm) and a footprint ranging from 180 to 360 m^2 (1,900 to 3,800 ft^2), depending on the number of extraction wells required. The preconceptual groundwater treatment process would be similar to that proposed for Alternative 4 and would involve clarification and multimedia filtration to remove any solids collected during groundwater extraction, liquid phase adsorption using GAC to remove TCE and other organics, and reverse osmosis and ion exchange for nitrate removal.

After construction of the extraction well network and associated groundwater treatment systems, the two systems would be carefully monitored on a regular basis and their performance evaluated. The time required for ex-situ treatment of extracted groundwater for Alternative 7 is predicted to require approximately 16 years, assuming a maximum TCE concentration of 9,000 µg/L. The actual performance in the field may vary from that assumed during design, given uncertainties about subsurface geology prior to construction and operation.

Because contaminants would remain in site groundwater at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

Similar to Alternative 2, groundwater monitoring would be conducted for contaminants other than TCE using the existing well network, as appropriate. This network could be expanded or reduced, depending on the results of future efforts to optimize the network for long-term monitoring. Similar to Alternative 2, this assessment assumed the installation and operation of additional monitoring wells equivalent to approximately 10% of the number of existing wells (i.e., about 15 additional wells). The exact monitoring network and details regarding frequency of sampling and parameters analyzed will be identified in the ROD or subsequent remedial design/remedial action reports for these operable units. The current groundwater monitoring program conducted by the DOE and DA consists of 73 wells at the WSCP and 79 wells at the WSOW, respectively. (The current [July 1997] monitoring program conducted by the DA sampled 49 wells and 6 springs.) Of these

wells, 10 monitor groundwater in the soil overburden. The remaining wells are screened in the bedrock system (Burlington/Keokuk, Fern Glen/Chouteau, Kimmswick, Joachim/St. Peter).

The monitoring program would continue for a reasonable period of time and would be evaluated during the review of the effectiveness of the remedy at least every five years, or until remediation goals identified in the ROD were achieved. Standard operating procedures used for the current monitoring activities would be expected to be adopted for the long-term monitoring effort. These monitoring efforts would include such activities as water-level measurements and the collection of quality assurance/quality control samples during each sampling event.

4.3.1 Overall Protection of Human Health and the Environment

Alternative 7 would actively remediate only TCE because TCE contamination of groundwater can be widespread and can continue for decades unless remediated. Alternative 7 would protect human health and the environment by remediating the contaminated groundwater so that when the remediation was complete. The TCE concentration in groundwater at the WSCP and the WSOW would be below the ARAR of 5 µg/L. In addition, TCE migration would be largely halted upon implementation of this alternative, and any potential future large-scale contamination by TCE of the aboveground springs would be effectively prevented. Alternative 7 might be expected to attain ARARs for TCE when remediation was completed.

Alternative 7 might be adequately protective of human health and the environment over the long term. Potential migration of the contamination toward the surface springs would be monitored. Data collected would identify the potential for continued migration and variations in local geochemical conditions that could affect natural removal of contaminants from groundwater via microbial biodegradation, photolysis, volatilization, sorption, and hydrolysis. Monitoring also tracks progress toward the attainment of remediation goals. Remediation of the water-bearing zone within the operable units would be provided by natural processes that are expected to attenuate contaminant concentrations. Dilution of the contaminated groundwater with uncontaminated groundwater drawn from infiltration of rainwater and runoff could also result in decreased concentrations.

4.3.2 Compliance with Potential ARARs

Compliance with potential ARARs for Alternative 7 would be similar to Alternative 2 (Section 4.2.2), except that Alternative 7 actively remediates groundwater that is contaminated above the ARAR for TCE (5 ug/L). Compliance with the TCE standard is potentially attainable, depending on the performance of Alternative 7. The performance of this alternative has been projected using certain assumptions that need further verification.

4.3.3 Long-Term Effectiveness and Permanence

Groundwater contaminated above the ARAR for TCE would be removed and treated under Alternative 7, which would provide for the reduction or elimination of potential risk associated with TCE levels currently found at the WSCP. The treatment system itself would be equipped with automated shutdown controls, secondary containment measures, and effluent concentration monitoring. These control measures would adequately protect human health and the environment should problems such as equipment failure, leaks, or spills arise.

Under current land use conditions, groundwater is not used and therefore poses no imminent risk to human health or the environment. Deed restrictions could be used to ensure that no new wells would be installed in the area of the contaminated groundwater, these restrictions could be difficult to enforce, however, without the application of additional controls (e.g., access restrictions). Additional protection for off-site residents is currently provided by quarterly sampling of off-site wells by the Missouri Department of Health. Continued federal ownership would eliminate any potential risks associated with on-property groundwater. Monitoring and maintenance activities would be carried out by the DOE and DA at these operable units for a reasonable period. Protection of human health and the environment in the extended future would be provided because monitoring activities by the DOE and DA would continue and allow consideration of contingency measures to protect human health and the environment. However, unacceptable impacts to human health and the environment would not be expected to occur. In addition, successful implementation of Alternative 7 would provide for the reduction or elimination of potential risk associated with TCE levels currently found at the WSCP.

4.3.3.1 Protection of Workers

Long-term monitoring and maintenance activities under Alternative 7 would be carried out for a reasonable period of time and would be evaluated during review of the effectiveness of the remedy at least every five years, or until remediation goals identified in the ROD were achieved. Workers would be present on-site periodically to perform these monitoring and maintenance activities. The potential impact on sampling personnel due to exposure to contaminants would be low.

The risks to workers associated with groundwater extraction, handling treatment residuals, and O&M of treatment process equipment would be low.

Groundwater extraction and treatment and monitoring activities over a 30-year period are estimated to result in approximately 16 to 21 cases of occupational injury, depending upon the number of extraction wells required and no occupational fatalities; these estimates are based on industry-specific statistics from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995). Standard operating procedures would be established to define proper treatment system operating parameters and maintenance requirements to ensure the safety and health of the workforce. Alternative 7 would, therefore, pose low long-term risks to workers.

4.3.3.2 Protection of the Public

Protection of the public, on a relative scale, would be better for Alternative 7 compared to Alternative 1. Following implementation of the 16-year groundwater extraction and treatment phase, Alternative 7 would provide for the reduction or elimination of potential risk associated with TCE levels currently found at the WSCP. Unacceptable risks to the general public would not be expected to occur under Alternative 7. Even if contaminant concentrations remained as they are now, the pathway for exposure to groundwater contamination is not complete (i.e., current and likely future land uses are considered to be recreational). However, with monitoring, information on future concentrations of contaminants in groundwater would be available to confirm this expectation.

4.3.3.3 Environmental Protection (Water Quality and Hydrology)

Water quality and hydrology, on a relative scale, would be better for Alternative 7 compared to Alternative 1, because the potential risk associated with TCE levels currently found at the WSCP would be reduced or eliminated.

4.3.4 Reduction of Toxicity, Mobility, or Volume through Treatment

Alternative 7 would satisfy the statutory preference for treatment as a principal element of remediation and provides reduction in toxicity, mobility, or volume of the contaminated groundwater through treatment. Alternative 7 reduces mobility by hydraulically controlling the migration of TCE-contaminated groundwater through extraction of contaminants. In addition, extraction and treatment of TCE-contaminated groundwater would also reduce the concentrations of other contaminants (e.g., nitrates and nitroaromatic compounds) that also exist in the TCE-contaminated groundwater at the WSCP near the raffinate pits area.

4.3.5 Short-Term Effectiveness

Risks to workers would be due primarily to physical hazards during construction activities. Construction activities are estimated to result in between 3 and 9 cases of occupational injury, depending on the number of extraction wells required and no occupational fatalities. This estimate is based on industry-specific statistics from the U.S. Bureau of Labor Statistics as reported by the National Safety Council (1995). Physical hazards would be minimized by adherence to stringent health and safety protocols.

Minimal environmental impacts would result from construction of the extraction well network and associated groundwater treatment facility. The primary impact to the environment would be associated with installation of the 200 to 650 extraction wells. These activities may result in physical disturbances of the habitat, but would be of short duration. Some short-term impacts might occur as a result of noise, exhaust fumes, and dust associated with any construction activities. Impacts to biological resources would be mitigated by avoiding unnecessary damage to vegetation, wildlife, and soil through controlling traffic and minimizing the area of disturbance.

During construction of the 200 to 650 extraction wells and associated groundwater treatment facility, the amount of criteria pollutants emitted as a result of equipment operations and

transportation (by car) of the construction personnel to the operable unit would be low (e.g., between 2,400 to 6,200 kg [5,400 to 14,000 lb] of CO emitted during the entire construction period) and as such, would not contribute to any off-site health impacts. Emissions of total suspended particulates (TSP) were (conservatively) estimated to be between approximately 29,000 to 74,000 kg (63,000 to 160,000 lb), assuming that all vehicles traveled over unpaved roads without any control measures. Vehicle traffic on unpaved surfaces, earthmoving, excavating, and bulldozing would be the major source of TSP. TSP generation during actual construction activities would be suppressed by watering, revegetation of bare areas, removing dirt and debris from the road surface, and using containment methods whenever feasible.

Accounting for transport of groundwater treatment residuals and worker commuter vehicles, the annual emission rate of criteria pollutants from worker vehicles would be low (e.g., between 240 to 340 kg [530 to 760 lb] per year of CO emitted) and would not contribute to any off-site health impacts. These temporary impacts would be limited to the immediate vicinity of the operable unit, and mitigative measures would be applied to ensure minimal impacts to off-site areas.

4.3.6 Implementability

Significant uncertainty is associated with the implementability of Alternative 7. Uncertainties are associated with the need for site (area)-specific hydrogeologic data to verify the appropriateness of assumptions used in the evaluations. One possible problem considered is the potential for the groundwater extraction system to not achieve the design flow rate of 1 L/s (0.3 gpm) for a single extraction well. This situation could result in schedule delays. Few implementability concerns associated with the groundwater extraction and treatment technologies would be posed by Alternative 7. Because groundwater extraction and treatment are well-developed technologies, technical problems are not likely to cause significant delays. Site operations would continue to use readily available resources for monitoring. Discharge of treated groundwater would likely require coordination with other agencies such as the EPA and the Missouri Department of Natural Resources.

Groundwater treatment services are commercially available; equipment and specialists are readily available within DOE and private industry. The groundwater treatment technologies considered for Alternative 7 are well developed and proven effective from SWTP operations. Further

development of these technologies would not be required before they could be applied at the site. Disposal services would be available within the WSSRAP on-site disposal cell.

Groundwater monitoring is readily implementable. Presently, numerous wells are located at these operable units, and additional wells could be easily installed and monitored. The ability to monitor any off-site plume migration is high. The existing network of monitoring wells would provide notice before any unacceptable exposure could occur.

The administrative feasibility of this alternative would be relatively straightforward. WSSRAP and remedial action project activities at the WSOW are coordinated with the State of Missouri and EPA Region VII. That coordination would continue during the duration of implementation. The implementation of this alternative would not require coordination with any other agencies beyond that already occurring, and no permit or license for on-site activities would be required.

4.3.7 Cost

Costs for this alternative would be associated with continuing the existing environmental monitoring program, constructing and operating groundwater extraction and treatment systems, and conducting a performance review at least every five years. Feasibility-level cost estimates were prepared using standard cost-estimating sources such as the latest version of the *Unit Price Book* developed by the U.S. Army Corps of Engineers (1989).

The estimated total and present-worth costs for Alternative 7 are given in Table 4.2; annual costs are estimated to range between $1 million and $2 million per year. The capital cost of Alternative 7 is estimated to range between $9 million and $25 million, depending on the number of extraction wells required (i.e., 200 to 650 wells). The capital cost would be primarily for installation of the 200 to 650 extraction wells.

Excluding the decontamination and decommissioning (D&D) costs of the groundwater treatment facility (which are highly speculative), the 30-year present worth of Alternative 7 is estimated to range from $23 million to $53 million.

The costs associated with potential future actions, in the event that potential migration of residual contamination did result in unacceptable exposure concentrations, were not quantified

because the uncertainty associated with these future activities precludes accurate assessment of these costs.

4.4 ALTERNATIVE 8: IN-SITU TREATMENT OF TCE USING IN-WELL VAPOR STRIPPING

The activities associated with Alternative 8 include the following:

- In-situ treatment of the groundwater primarily at the WSCP near the raffinate pits area contaminated with TCE to achieve a maximum TCE groundwater concentration of 5 μg/L;
- Source-control response actions implemented per RODs for the WSCP and the WSOW that would prevent further release of contaminants to groundwater;
- Performance monitoring of groundwater to verify that future contaminant concentrations would not result in unacceptable risks to human health;
- Institutional controls to ensure that contaminated groundwater was not used before protective concentrations were attained; and
- Contingency measures in the event that natural processes did not result in acceptable off-site concentrations and exposure.

In-well vapor stripping technology involves the creation of a groundwater circulation pattern and simultaneous aeration within the vapor stripping well to volatilize the TCE from the circulating groundwater. This alternative would actively remediate the TCE-contaminated groundwater that has been identified near the raffinate pits area of the WSCP. This alternative, however, would not address the nitrates and nitroaromatic compounds that may also be present. An approach identical to that described in Alternative 2 would be applied to manage other contaminants in the groundwater. This alternative provides for active remediation of TCE only. As in Alternatives 2 and 7, long-term monitoring would be conducted in order to obtain data that would verify decreasing nitrates and nitroaromatic concentrations with time. This decrease is expected to result from source removals and from continued occurrence of natural attenuation processes.

The in-well vapor stripping technology consists primarily of a screened well submerged beneath the water table and an air line within the well extending to below the water table. A compressor delivers air or an inert gas such as nitrogen to the water column, thereby aerating the water within the well. The gas bubbles cause the water within the well to be less dense than the nonaerated water outside. As a result, the dense water flows in through the well screen and forces the aerated water upward within the well. The result is a rising column of aerated water within the well, which forms an air lift pumping system.

After construction of the in-well vapor stripping network and associated groundwater treatment systems, the two systems would be carefully monitored on a regular basis and their performance evaluated. The time required for in-situ treatment for Alternative 8 is predicted to require from two to three years, assuming that water can be stripped of 90% of its VOCs with one pass through a vapor stripping well (Cichon, et al. 1997; HazTECH, 1997). The actual performance in the field may vary from that assumed during design, given uncertainties about subsurface geology prior to construction and operation.

Because contaminants would remain in site groundwater at concentrations above levels that allow for unlimited use and unrestricted exposure, reviews would be conducted at least every five years to ensure that the remedy continued to provide adequate protection of human health and the environment.

Similar to Alternative 2, groundwater monitoring would be conducted for contaminants other than TCE using the existing well network, as appropriate. This network could be expanded or reduced, depending on the results of future efforts to optimize the network for long-term monitoring. Similar to Alternative 2, this assessment assumed the installation and operation of additional monitoring wells equivalent to approximately 10% of the number of existing wells (i.e., about 15 additional wells). The exact monitoring network and details regarding frequency of sampling and parameters analyzed will be identified in the ROD or subsequent remedial design/remedial action reports for these operable units. The current groundwater monitoring program conducted by the DOE and DA consists of 73 wells at the WSCP and 79 wells at the WSOW, respectively. (The current [July 1997] monitoring program conducted by the DA sampled 49 wells and 6 springs.) Of these wells, 10 monitor groundwater in the soil overburden. The remaining wells are screened in the bedrock system (Burlington/Keokuk, Fern Glen/Chouteau, Kimmswick, Joachim/St. Peter).

The monitoring program would continue for a reasonable period of time and would be evaluated during the review of the effectiveness of the remedy at least every five years, or until remediation goals identified in the ROD were achieved. Standard operating procedures used for the current monitoring activities would be expected to be adopted for the long-term monitoring effort. These monitoring efforts would include such activities as water-level measurements and the collection of quality assurance/quality control samples during each sampling event.

4.4.1 Overall Protection of Human Health and the Environment

Similar to Alternative 7, Alternative 8 would actively remediate only TCE because TCE contamination of groundwater can be widespread and can continue for decades unless remediated. Alternative 8 would protect human health and the environment by remediating the contaminated groundwater so that when the remediation was complete, the TCE concentration in groundwater at the WSCP and WSOW would be below the ARAR of 5 µg/L. In addition, TCE migration would be largely halted upon implementation of this alternative, and any potential future large-scale contamination by TCE of the aboveground springs would be effectively prevented. Alternative 8 might be expected to attain ARARs for TCE when remediation was completed.

Alternative 8 might be adequately protective of human health and the environment over the long term. Potential migration of the contamination toward the surface springs would be monitored. Data collected would identify the potential for continued migration and variations in local geochemical conditions that could affect natural removal of contaminants from groundwater via microbial biodegradation, photolysis, volatilization, sorption, and hydrolysis. Monitoring also tracks progress toward the attainment of remediation goals. Remediation of the water-bearing zone within the operable units would be provided by natural processes that are expected to attenuate contaminant concentrations. Dilution of the contaminated groundwater with uncontaminated groundwater drawn from infiltration of rainwater and runoff could also result in decreased concentrations.

4.4.2 Compliance with Potential ARARs

Compliance with potential ARARs for Alternative 8 would be similar to Alternative 7 (Section 4.3.2). Compliance with the TCE standard is potentially attainable, depending on the

performance of Alternative 8. The performance of this alternative has been projected using certain assumptions that need further verification.

4.4.3 Long-Term Effectiveness and Permanence

Similar to Alternative 7, groundwater contaminated above the ARAR for TCE would be treated under Alternative 8, which would provide for the reduction or elimination of potential risk associated with TCE levels currently found at the WSCP. The treatment system itself would be equipped with automated shutdown controls, secondary containment measures, and effluent concentration monitoring. These control measures would adequately protect human health and the environment should problems such as equipment failure, leaks, or spills arise.

Under current land use conditions, groundwater is not used and therefore poses no imminent risk to human health or the environment. Deed restrictions could be used to ensure that no new wells would be installed in the area of the contaminated groundwater; these restrictions, however, could be difficult to enforce without the application of additional controls (e.g., access restrictions). Additional protection for off-site residents is currently provided by quarterly sampling of off-site wells by the Missouri Department of Health. Continued federal ownership would eliminate any potential risks associated with on-property groundwater. Monitoring and maintenance activities would be carried out by the DOE and DA at these operable units for a reasonable period. Protection of human health and the environment in the extended future would be provided because monitoring activities by the DOE and DA would continue and allow consideration of contingency measures to protect human health and the environment. However, unacceptable impacts to human health and the environment would not be expected to occur. In addition, successful implementation of Alternative 8 would provide for the reduction or elimination of potential risk associated with TCE levels currently found at the WSCP.

4.4.3.1 Protection of Workers

Long-term monitoring and maintenance activities under Alternative 8 would be carried out for a reasonable period of time and would be evaluated during review of the effectiveness of the remedy at least every five years, or until remediation goals identified in the ROD were achieved. Workers would be present on-site periodically to perform these monitoring and maintenance

activities. The potential impact on sampling personnel due to exposure to contaminants would be low.

The risks to workers associated with the in-well vapor stripping technology, handling treatment residuals, and O&M of GAC off-gas treatment process equipment would be low.

In-well vapor stripping and off-gas treatment and monitoring activities over a 30-year period are estimated to result in less than nine cases of occupational injury, depending on the number of in-well vapor stripping wells required and no occupational fatalities; these estimates are based on industry-specific statistics from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995). Standard operating procedures would be established to define proper treatment system operating parameters and maintenance requirements to ensure the safety and health of the workforce. Alternative 8 would, therefore, pose low long-term risks to workers.

4.4.3.2 Protection of the Public

Protection of the public, on a relative scale, would be similar to Alternative 8 compared to Alternative 7. Following implementation of the two- to three-year groundwater extraction and treatment phase, Alternative 8 would provide for the reduction or elimination of potential risk associated with TCE levels currently found at the WSCP. Unacceptable risks to the general public would not be expected to occur under Alternative 8. Even if contaminant concentrations remained as they are now, the pathway for exposure to groundwater contamination is not complete (i.e., current and likely future land uses are considered to be recreational). However, with monitoring, information on future concentrations of contaminants in groundwater would be available to confirm this expectation.

4.4.3.3 Environmental Protection (Water Quality and Hydrology)

Water quality and hydrology for Alternative 8 would be similar, on a relative scale, compared to Alternative 7 because the potential risk associated with TCE levels currently found at the WSCP would be reduced or eliminated.

4.4.4 Reduction of Toxicity, Mobility, or Volume through Treatment

Alternative 8 would satisfy the statutory preference for treatment as a principal element of remediation and provides reduction in toxicity, mobility, or volume of the contaminated groundwater through treatment. Alternative 8 reduces mobility by hydraulically controlling migration of TCE-contaminated groundwater through extraction of contaminants. However, compared to Alternative 7, Alternative 8 would not reduce the concentrations of other contaminants (e.g., nitrates and nitroaromatic compounds) that also exist in the TCE-contaminated groundwater at the WSCP near the raffinate pits area.

4.4.5 Short-Term Effectiveness

Risks to workers would be due primarily to physical hazards during construction activities. Construction activities are estimated to result in less than two cases of occupational injury, depending on the number of vapor stripping wells required, and no occupational fatalities. This estimate is based on industry-specific statistics from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995). Physical hazards would be minimized by adherence to stringent health and safety protocols.

Minimal environmental impacts would result from construction of the vapor stripping well network and associated off-gas treatment facility. The primary impact to the environment would be associated with installation of the vapor stripping wells. These activities may result in physical disturbances of the habitat, but would be of short duration. Some short-term impacts might occur as a result of noise, exhaust fumes, and dust associated with any construction activities. Impacts to biological resources would be mitigated by avoiding unnecessary damage to vegetation, wildlife, and soil through controlling traffic and minimizing the area of disturbance.

During construction of the vapor stripping wells and associated off-gas treatment facility, the amount of criteria pollutants emitted as a result of equipment operations and transportation (by car) of the construction personnel to the operable unit would be low (e.g., between 60 and 1,000 kg [between 1,400 and 2,100 lb] of CO emitted during the entire construction period) and as such, would not contribute to any off-site health impacts. Emissions of TSP were (conservatively) estimated to be between approximately 7,700 and 11,000 kg (17,000 and 24,000 lb), assuming that all vehicles traveled over unpaved roads without any control measures. Vehicle traffic on unpaved

surfaces, earthmoving, excavating, and bulldozing would be the major source of TSP. TSP generation during actual construction activities would be suppressed by watering, revegetation of bare areas, removing dirt and debris from the road surface, and using containment methods whenever feasible.

Accounting for transport of groundwater treatment residuals and worker commuter vehicles, the annual emission rate of criteria pollutants from worker vehicles would be low (e.g., less than 50 kg [100 lb] per year of CO emitted) and would not contribute to any off-site health impacts. These temporary impacts would be limited to the immediate vicinity of the operable unit, and mitigative measures would be applied to ensure minimal impacts to off-site areas.

4.4.6 Implementability

Significant uncertainty is associated with the implementability of Alternative 8. Uncertainties are associated with the need for site- (area) specific hydrogeologic data to verify the appropriateness of assumptions used in the evaluations. One possible problem considered is whether the required number of recirculations would be achieved given the heterogeneity of the TCE-contaminated zone. This situation could result in schedule delays and/or unsuccessful implementation of this innovative technology. A number of implementability concerns associated with the in-well vapor stripping technology would be posed by Alternative 8. Because in-well vapor stripping is not a well-developed technology, technical problems could be likely to cause significant delays. Site operations would continue to use readily available resources for monitoring.

Off-gas treatment services are commercially available; equipment and specialists are readily available within DOE and private industry. The off-gas treatment technology considered for Alternative 8 is well developed and proven effective. Further development of this technology would not be required before they can be applied at the site. Disposal services would be available within the WSSRAP on-site disposal cell.

Groundwater monitoring is readily implementable. Presently, numerous wells are located at these operable units, and additional wells could be easily installed and monitored. The ability to monitor any off-site plume migration is high. The existing network of monitoring wells would provide notice before any unacceptable exposure could occur.

The administrative feasibility of this alternative would be relatively straightforward. WSSRAP and remedial action project activities at the WSOW are coordinated with the State of Missouri and EPA Region VII. That coordination would continue during the duration of implementation. The implementation of this alternative would not require coordination with any other agencies beyond that already occurring, and no permit or license for on-site activities would be required.

4.4.7 Cost

Costs for this alternative would be associated with continuing the existing environmental monitoring program, constructing and operating the in-well vapor stripping and associated off-gas and treatment systems, and conducting a performance review at least every five years. Feasibility-level cost estimates were prepared using standard cost-estimating sources such as the latest version of the *Unit Price Book* developed by the U.S. Army Corps of Engineers (1989).

The estimated total and present-worth costs for Alternative 8 are given in Table 4.3; annual costs are estimated to be approximately $0.5 million per year. The capital cost of Alternative 8 is estimated to range between $1 and $3 million, depending on the number of vapor stripping wells. The capital cost would be primarily for installation of the vapor stripping and monitoring wells.

Excluding the D&D costs of the in-well vapor stripping network (which are highly speculative), the 30-year present worth of Alternative 8 is estimated to range from $5 million to $7 million.

The costs associated with potential future actions, in the event that potential migration of residual contamination did result in unacceptable exposure concentrations, were not quantified because the uncertainty associated with these future activities precludes accurate assessment of these costs.

TABLE 4.2 Cost Estimate for Alternative 7

Activity	Estimated Cost ($ million)
Extraction well and groundwater treatment facility construction[a]	9 to 25
Extraction well and groundwater treatment facility operations	13 to 31
Groundwater monitoring[b]	9
Total[b]	32 to 65
Present worth [b]	21 to 47

[a] Based upon construction of between 200 to 650 extraction wells

[b] Estimated upper-bound cost for a 30-year period, assuming annual sampling frequency for the existing network of monitoring wells. Any reduction in duration of monitoring, sampling frequency, or number of wells sampled would result in a proportional reduction in cost.

TABLE 4.3 Cost Estimate for Alternative 8

Activity	Estimated Cost ($ million)
Vapor stripping well and off-gas treatment facility construction[a]	1 to 3
Vapor stripping well and off-gas treatment facility operations	0.5
Groundwater monitoring[b]	9
Total[b]	11 to 12
Present worth [b]	6 to 7

[a] Based upon construction of between 9 to 16 vapor stripping and associated monitoring wells

[b] Estimated upper-bound cost for a 30-year period, assuming annual sampling frequency for the existing network of monitoring wells. Any reduction in duration of monitoring, sampling frequency, or number of wells sampled would result in a proportional reduction in cost.

5 COMPARATIVE ANALYSIS OF ALTERNATIVES

A comparison of the alternatives with regard to the nine evaluation criteria listed in Chapter 4 is presented in Sections 5.1 and 5.2. These criteria are categorized into the following three groups as stipulated in the NCP: threshold criteria, primary balancing criteria, and modifying criteria.

The threshold category contains the two criteria that each alternative must meet to be eligible for selection:

- Overall protection of human health and the environment; and
- Compliance with ARARs, unless a waiver condition applies.

These threshold criteria ensure that the remedial action selected will be protective of human health and the environment and that the action will attain the ARARs identified at the time of the ROD or that it provides grounds for obtaining a waiver.

The primary balancing category contains the five criteria that are used to assess the relative advantages and disadvantages of each alternative to determine which is most appropriate:

- Long-term effectiveness and permanence;
- Reduction of toxicity, mobility, or volume through treatment;
- Short-term effectiveness;
- Implementability; and
- Cost.

The first two criteria consider the preference for treatment as a principal element and the bias against off-site land disposal of untreated waste. Cost-effectiveness is determined by evaluating the following three of the five balancing criteria: long-term effectiveness and permanence; reduction of toxicity, mobility, or volume through treatment; and short-term effectiveness. Overall effectiveness is then compared with cost to ensure that the costs are proportional to the overall effectiveness of a remedial action.

The modifying category consists of two criteria that are considered in remedy selection and that will be addressed in the responsiveness summary and ROD to be prepared following the public comment period for this FS:

- State acceptance: and
- Community acceptance.

The two modifying criteria are not addressed in this comparative analysis.

The four final alternatives retained after screening are compared in Sections 5.1 and 5.2 for the threshold and primary balancing criteria, respectively. The results of this comparison are provided in Table 5.1.

5.1 THRESHOLD CRITERIA

5.1.1 Overall Protection of Human Health and the Environment

Alternative 1 might be adequately protective of human health and the environment in both the short term and long term. Under current land-use conditions, the contaminated groundwater at the WSCP and the WSOW poses no imminent risk to human health or the environment at the surface springs. Future land-use conditions are expected to be similar to current conditions.

Alternative 2 might also be protective of human health and the environment over the long term. Monitoring and investigative activities by the DOE and DA would identify any potential future migration and variations in local geochemical conditions (such as Eh and pH) that could adversely affect removal of the contaminants from the groundwater by absorption, adsorption, biodegradation, and other natural processes. The results from monitoring activities would be used to assess the attainment of remediation goals. Chemical distribution in the water-bearing zone could also be tracked.

The possibility of continued federal ownership of the WSTA at the WSOW and the area containing the on-site disposal cell at the WSCP would restrict site development activities through the rights of ownership, so that on-property development activities such as agricultural or residential usage could be restricted or eliminated. As with Alternative 1, unacceptable impacts to human health and the environment would not be expected to occur.

TABLE 5.1 Comparative Analysis of Alternatives

Criterion	Alternative 1: No Action	Alternative 2: Monitoring with No Active Remediation	Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater	Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping
Overall protection of human health and the environment	Would be adequately protective of human health and the environment in both the short and long term.	Would provide protection similar to Alternative 1; however, monitoring and investigative activities would verify that contaminant concentrations decrease with time. Contaminant distribution in the water-bearing zone would be tracked.	Would provide adequate protection of human health and the environment in both the short and long term. Monitoring activities would also provide data to verify expected decreases of other contaminant concentrations in the future. It is expected that overall remaining contaminant concentrations would decrease as a result of source removals and the occurrence of natural processes.	Similar to Alternative 7.
Compliance with ARARs	Would not attain certain applicable requirements, such as standards for levels of TCE, nitrates, and nitroaromatic compounds in groundwater for a long time period. A waiver would be pertinent from the applicable limits for TCE, nitrates, and nitroaromatic compounds on the basis of technical impracticability.	Would not attain certain applicable requirements such as standards for levels of TCE, nitrates, and nitro-aromatic compounds in groundwater. A waiver would be pertinent from the applicable limits for TCE, nitrates, and nitroaromatic compounds on the basis of technical impracticability. Five-year reviews of the effectiveness and protectiveness of the response would be conducted because contaminants would remain on-site at concentrations above levels that allow for unlimited use and unrestricted exposure.	Would not directly attain certain applicable requirements such as standards for levels of nitrates and nitroaromatic compounds in groundwater. A waiver would be pertinent from the applicable limits for nitrates and nitroaromatic compounds on the basis of technical impracticability. Five-year review of the effectiveness and protectiveness of the response would be conducted because contaminants other than TCE would remain on-site at concentrations above levels that allow for unlimited use and unrestricted exposure.	Similar to Alternative 7.

TABLE 5.1 (Cont.)

Criterion	Alternative 1: No Action	Alternative 2: Monitoring with No Active Remediation	Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater	Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping
Long-term effectiveness and permanence	Investigative and monitoring activities would not be performed. Would not address the potential for further management of the groundwater in the case where unacceptable impacts to human health and the environment might occur in the future, i.e., at the surface springs.	Would provide adequate and reliable verification monitoring of the groundwater within the operable unit. Would provide long-term effectiveness by providing data to allow consideration of other management procedures such as institutional controls.	Would provide adequate and reliable verification monitoring of the groundwater. Would provide long-term effectiveness by monitoring to allow consideration of further management options, including institutional controls that limit access and use of groundwater, as appropriate.	Similar to Alternative 7.
Reduction of toxicity, mobility, or volume through treatment	Not applicable because the contaminated groundwater would not be treated. Restoration of the water-bearing zone within the operable unit would be provided by natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials and by dilution of the contaminated groundwater with uncontaminated groundwater drawn through infiltration of rainwater and runoff.	Not applicable because the contaminated groundwater would not be treated. Restoration of the water-bearing zone within the operable unit would be provided by natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials and by dilution of the contaminated groundwater with uncontaminated groundwater drawn through infiltration of rainwater and runoff.	Reduction of the toxicity, mobility, or volume associated with TCE contamination at the WSCP would be accomplished. Further restoration of the water-bearing zone within the operable unit would be provided by natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials and dilution of the contaminated groundwater with uncontaminated groundwater drawn through infiltration of rainwater and runoff.	Similar to Alternative 7.
Short-term effectiveness	No potential impacts on workers or the environment because no activities would be undertaken.	Expected to be low, with less than one case of occupational injury and no occupational fatalities during proposed monitoring well construction. Any potential short-term environmental impacts would be limited to the immediate vicinity of the operable unit, and mitigative measures would be applied to ensure minimal impacts to off-site areas.	Expected to be low, with less than 9 cases of occupational injury and no occupational fatalities during operations and well construction activities. Any potential short-term environmental impacts would be limited to the immediate vicinity of the operable unit, and mitigative measures would be applied to ensure minimal impacts to off-site areas.	Similar to Alternative 7.

TABLE 5.1 (Cont.)

Criterion	Alternative 1: No Action	Alternative 2: Monitoring with No Active Remediation	Alternative 7: Removal and Ex-Situ Treatment of TCE-Contaminated Groundwater	Alternative 8: In-Situ Treatment of TCE Using In-Well Vapor Stripping
Implementability	No implementability concerns because no action would be taken nor would any future activities be considered.	Few implementability concerns because of the limited actions taken. Current monitoring operations would continue with the use of readily available resources.	Uncertainties with implementation of this alternative are associated with need for location (or area) specific hydrogeologic data to verify the appropriateness of assumptions applied in the evaluations.	Similar to Alternative 7.
Cost	Total cost lowest in the short term ($0), but the comparative level of effectiveness would be low. Cost could be potentially higher in the long term if conditions worsened considerably over time and expensive emergency and/or expanded response became necessary.	Could be considered to be the most cost-effective alternative because it would provide overall protection of human health and the environment for a reasonable cost. Costs would be associated with continuing the existing environmental monitoring program, constructing and operating the proposed new monitoring wells, and conducting a performance review at least every five years. Could be implemented with existing resources and maintained at a relatively low cost.	Capital cost estimated to range between $9 million to $25 million; assuming monitoring for 30 years, the 30-year present worth cost is estimated to range between $23 million to $53 million. This alternative is the most costly of the four alternatives considered.	Capital cost estimated to range between $1 million to $3 million; assuming monitoring for 30 years, the 30-year present worth cost is estimated to range between $5 million to $7 million.

Under Alternatives 1 and 2, the currently contaminated groundwater would not be removed or treated. Alternatives 7 and 8 would protect human health and the environment by remediating the TCE from the contaminated groundwater so that when the remediation was complete, the TCE concentration in groundwater at the WSCP and the WSOW would be at or below the ARAR of 5 µg/L. The overall protection of the environment in the long term would be provided through restoration of the water-bearing zone at the WSCP and the WSOW. Naturally occurring processes, including dilution of the contaminated groundwater with uncontaminated groundwater drawn through infiltration of rainwater and runoff, are expected to attenuate contaminant concentrations.

5.1.2 Compliance with ARARs

A comprehensive list of potential standards is presented in Appendix A. The potential standards for each alternative are discussed in detail in Chapter 4. Alternative 1 would not attain certain relevant and appropriate requirements, such as standards for levels of TCE and nitrates in groundwater. Alternative 2 would also not meet certain standards; however, a technical impracticability waiver could be requested to allow the establishment of revised remediation goals that would be attainable but still protective of human health and the environment. For Alternatives 7 and 8, a waiver would be requested granting relief from the response objective of returning the groundwater within the WSCP and the WSOW to beneficial use (aquifer restoration). A technical impracticability waiver was not considered for Alternative 1 because it would not involve technical action.

A request for a technical impracticability waiver would include an evaluation of the proposed alternative remedy and other available conventional and innovative technologies, including the length of time required to achieve existing remediation goals and the costs of construction and operations. In general, the estimated duration to achieve remediation goals by treatment would be longer than the 100-year reasonable amount of time considered by the EPA. Alternative 2, which is conservatively based on the assumed construction of additional monitoring wells and an assumed operations duration of at least 10 years, would cost $3.9 million (in current 1997 dollars) over the 10-year period, with a present worth of approximately $2.8 million. If future groundwater monitoring would be conducted using the existing well network without any additional well construction, the cost (in current 1997 dollars) of Alternative 2 would decrease to approximately $3.1 million, with a present worth of approximately $2.2 million. The 30-year present-worth cost

for Alternative 7 would range from $23 to $53 million. For Alternative 8, the 30-year present-worth cost would range from $5 million to $7 million (Appendix E).

Protection of human health and the environment would be provided because contaminant concentrations would be expected to decrease following source removals at both areas. In addition, potential risk from TCE would be reduced or eliminated depending on performance of Alternatives 7 and 8. The groundwater currently poses no imminent risk to human health or the environment at the springs. In the future, the concentration of contaminants will continue to decrease due to existing natural processes such as transformation, transfer, and dilution through infiltration of rainwater and runoff. The following measures might be included in the waiver to ensure protection of human health and the environment:

- Continued operation of the existing groundwater monitoring system; and
- Consideration of the installation of additional groundwater monitoring wells, if appropriate, pending the ROD or subsequent remedial design/remedial action reports for this operable unit.

The effectiveness of the remedy at the operable units would be reviewed at least every 5 years for Alternatives 2, 7, and 8 because contaminants would remain on-site at levels above unlimited use and unrestricted exposure.

5.2 PRIMARY BALANCING CRITERIA

5.2.1 Long-Term Effectiveness and Permanence

Alternative 1 does not include investigative and monitoring activities to verify long-term effectiveness. Under current conditions, the contaminated groundwater at the WSCP and the WSOW poses no imminent risk to human health and the environment. Although contaminant concentrations would not be measured by the DOE and DA in the future, it is expected that unacceptable impacts to human health and the environment would not occur. However, Alternative 1 does not address the potential for implementation of any contingency response measures if unacceptable impacts to human health and environment did occur (e.g., prevent or limit access and use of the contaminated groundwater if contaminant concentrations remained at current levels).

Under Alternatives 2, 7, and 8, monitoring and maintenance activities would be carried out at the WSCP and the WSOW for a reasonable period, to be evaluated during review of the effectiveness of the remedy at least every 5 years, or until remediation goals identified in the ROD were achieved; thus, these activities would provide adequate and reliable controls to manage the groundwater within these areas. Long-term effectiveness of Alternatives 2, 7, and 8 would be ensured because investigative and monitoring activities would continue, thereby allowing consideration of contingency response measures in the future, if appropriate.

5.2.2 Reduction of Toxicity, Mobility, or Volume through Treatment

Reduction of toxicity, mobility, and volume through treatment is not applicable to either Alternative 1 or 2 because the contaminated groundwater would not be treated under either alternative. Restoration of the water-bearing zone within the WSCP and the WSOW would be provided by natural processes such as biodegradation, adsorption, and chemical reactions with subsurface materials and by dilution of the contaminated groundwater with uncontaminated groundwater drawn through infiltration of rainwater and runoff.

Alternatives 7 and 8 would satisfy the statutory preference for treatment as a principal element of remediation and provide reduction in toxicity, mobility, and volume of the contaminated groundwater through treatment. Alternative 7 reduces mobility by hydraulically controlling migration of TCE-contaminated groundwater through extraction of contaminants.

5.2.3 Short-Term Effectiveness

For Alternative 1, conditions would essentially remain the same in the short term, and no significant changes in potential exposures would be expected because no activities would be undertaken. No potential impacts would occur to workers or the environment under Alternative 1.

The short-term impacts for Alternative 2 would be expected to be low, with less than one case of occupational injury and no occupational fatalities during proposed monitoring well construction. Potential short-term environmental impacts resulting from implementation of Alternative 2 would be limited to the immediate vicinity of the operable units, and mitigative measures would be applied to ensure minimal impacts to off-site areas.

For Alternatives 7 and 8, short-term impacts from construction activities are estimated to result in less than nine cases of occupational injury, depending on the number of extraction wells required; in addition, no occupational fatalities are predicted. This estimate is based on industry-specific statistics from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995). Physical hazards would be minimized by adherence to stringent health and safety protocols.

5.2.4 Implementability

No implementability concerns would be posed by Alternative 1 because no action would be taken nor would any future activities be considered. Alternative 2 would pose few implementability concerns because resources would be readily available for groundwater monitoring and additional wells could be easily installed, if appropriate. Monitoring the effectiveness of Alternative 2 would be relatively easy to implement. The administrative feasibility of Alternative 2 would be relatively straightforward, and no permits or licenses for on-site activities would be required.

Significant uncertainty is associated with the implementability of Alternatives 7 and 8. Uncertainties are associated with the need for site (area) specific hydrogeologic data to verify the appropriateness of assumptions used in the evaluations.

5.2.5 Cost

Alternative 1 would be the least expensive alternative in the short term. Because no activities would be undertaken, there would be no present-worth, capital, or annual O&M costs. However, total costs could be highest in the long term if contaminated groundwater from the WSCP and the WSOW traveled to the surface springs in high concentrations. Because all monitoring and investigative activities by the DOE and DA would have ceased, conditions could have worsened considerably over time, necessitating an expensive emergency and/or expanded response in the future. Thus, the cost-effectiveness of the no-action alternative can be considered to be low in the long term.

Preliminary costs were estimated for Alternative 2 for comparative purposes. Final costs would be developed during the detailed design stage following remedy selection. The total cost, long-term monitoring costs, and present-worth costs for Alternative 2 are summarized in Table 4.1.

Compared with Alternative 1, Alternative 2 is considered to be the more cost-effective alternative because it would provide overall protection of human health and the environment for a reasonable cost. Costs for Alternative 2 would be associated with continuing the existing environmental monitoring program, constructing and operating any proposed new monitoring wells, and conducting a performance review at least every 5 years. Alternative 2 could be implemented with existing resources and maintained at a relatively low cost.

Costs associated with Alternative 7 are highest, with capital costs estimated to range from $9 million to $25 million. For Alternative 8, capital costs are estimated to range between $1 million and $3 million. Because of uncertainties associated with the implementation of Alternatives 7 and 8, it is difficult to determine the cost-effectiveness associated with these two alternatives.

5.3 SUMMARY

In summary, Alternative 1 does not satisfy the threshold criteria for protecting human health and the environment and complying with PRGs. Alternatives 2, 7, and 8 do satisfy the threshold criteria, with waivers as appropriate. In addition, these alternatives would provide long-term protection of human health and the environment in the extended future because investigative and monitoring activities would continue and would allow consideration of contingency response measures in the future if contaminant concentrations are identified at unacceptable levels and access and use of contaminated groundwater occurred. Any short-term impacts associated with Alternatives 2, 7, and 8 would be temporary and limited to the immediate vicinity of the operable units, and mitigative measures would be applied to ensure minimal impacts to off-site areas. Implementation of monitoring activities associated with Alternatives 2, 7, and 8 would be straightforward because it would involve use of the groundwater monitoring system established at the WSCP and the WSOW and would not require any permits or licenses for on-site activities. Implementation of Alternatives 7 and 8 is not as certain as implementation of Alternative 2 because of the uncertainties associated with the need for location (area) specific hydrogeologic data (e.g., hydraulic conductivity and sustainable pump rates) to verify the appropriateness of assumptions used

in the evaluations. Alternative 2 is considered to be more cost-effective than Alternative 1 because it would provide overall protection of human health and the environment for a reasonable cost. However, the cost-effectiveness of Alternatives 7 and 8 is difficult to determine because of uncertainties related to their implimentation.

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APPENDIX A:

REGULATORY REQUIREMENTS POTENTIALLY APPLICABLE OR RELEVANT AND APPROPRIATE TO THE REMEDIAL ACTION

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The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation of potential alternatives for addressing groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively, in St. Charles County, Missouri. This appendix discusses the regulatory requirements that are potentially applicable or relevant and appropriate to the remedial action.

A.1 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has promulgated implementing regulations for the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended; these regulations are presented in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (Title 40, Part 300, *Code of Federal Regulations* [40 CFR Part 300]). This feasibility study (FS) follows the feasibility study process for sites on the National Priorities List (NPL). Under this process, remedial alternatives for the groundwater operable units at the WSCP and the WSOW were developed on the basis of remediation goals and potentially suitable technologies. The short-term and long-term aspects of three criteria (effectiveness, implementability, and cost) guided, as appropriate, the development and screening of alternatives. Alternatives that remained after this initial screening underwent a detailed analysis in which the individual alternatives were assessed according to nine evaluation criteria, including compliance with "applicable or relevant and appropriate requirements" (ARARs).

The NCP specifies that the evaluation of alternatives for remedial action at an NPL site must include an assessment of whether the alternatives will attain ARARs under federal environmental laws and state environmental or facility siting laws or grounds for invoking one of the waivers (40 CFR 300.430(e)(9)(iii)(B)) must be provided. To be eligible for selection as the remedy for an NPL site, an alternative must attain ARARs unless a waiver is appropriate (40 CFR 300.430(f)(1)(i)(A)). Other advisories, criteria, or guidance developed by the EPA, other federal agencies, or states, which might be useful for developing the remedy for an NPL site, can also be

considered as part of the evaluation (40 CFR 300.400(g)(3)). These other measures are called "to-be-considered," or TBC, requirements.

The ARARs are standards properly promulgated under federal or state statutes that might be applicable or relevant and appropriate to all or part of the action. Only those state requirements that are (1) promulgated such that they are of general applicability and legally enforceable, (2) identified by the state in a timely manner, and (3) more stringent than federal requirements will be considered ARARs (40 CFR 300.400(g)(4)). TBCs are standards or guidelines that have not been properly promulgated (i.e., a process including publication, comment, and formal adoption under applicable federal or state administrative regulations). TBCs would include DOE Orders or proposed state or federal agency regulations that might be pertinent to the action being considered. In addressing a requirement that might affect a remedial action being considered for a site, a determination is made regarding its relationship to (1) the location of the action; (2) the contaminants involved; and (3) the specific components of the action, such as factors unique to a certain technology.

Any regulation, standard, requirement, criterion, or limitation under any federal or state environmental law or state facility siting law may be either applicable or relevant and appropriate to a remedial action, but not both. Applicable requirements are cleanup standards; standards of control; or other substantive environmental protection requirements, criteria, or limitations promulgated under federal or state laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance at a CERCLA site (40 CFR 300.5). Relevant and appropriate requirements are cleanup standards, standards of control, or other substantive environmental protection requirements, criteria, or limitations promulgated under federal or state laws that are not applicable but that address problems or situations sufficiently similar to those encountered at the CERCLA site that their use is well suited to the particular site (40 CFR 300.5). If the requirement is not legally applicable to the remedial action, a determination must be made as to whether the requirement is both relevant and appropriate. For this determination, the requirement must be considered sufficiently similar to the circumstances of the action, and it must

also be well suited to the site. Under the NCP, the following comparisons must be made to determine relevance and appropriateness:

- The purpose of the requirement and the purpose of the CERCLA action;
- The medium regulated or affected by the requirement and the medium contaminated or affected at the CERCLA site;
- The substances regulated by the requirement and the substances found at the CERCLA site;
- The actions or activities regulated by the requirement and the remedial action considered for the CERCLA site;
- Any variance, waivers, or exemptions for the requirement and their availability for the circumstances at the CERCLA site;
- The type of place regulated and the type of place affected by the release or CERCLA action;
- The type and size of structure or facility regulated and the type and size of structure or facility affected by the release or considered by the CERCLA site;
- Any consideration of use or potential use of affected resources in the requirement and the use or potential use of the affected resource at the CERCLA site.

On-site actions must comply with all substantive provisions of an ARAR, but not with related administrative and procedural requirements (e.g., filing reports or obtaining a permit). Off-site actions must comply only with requirements that are legally applicable, but must comply with both substantive and administrative parts of those requirements. On-site actions include actions in the areal extent of contamination and all suitable areas in very close proximity to the contamination that are part of the response action. These actions would include any activities within the WSCP and WSOW areas and other areas contaminated by the migration of a hazardous substance, pollutant, or contaminant from any of the areas under the custody and accountability of DOE (EPA 1995).

Potential TBC requirements are typically considered only if no promulgated requirements exist that are either applicable or relevant and appropriate. TBCs are to be used on an "as appropriate" basis, such as when ARARs do not exist for a contaminant or circumstance (EPA 1990, p. 8745). Because the Weldon Spring site is a DOE facility, applicable DOE Orders, standards, and guidance will be followed, irrespective of their TBC designation under the ARAR process.

For groundwater remedial actions, CERCLA Section 121(d) states that a remedial action will attain a level or standard of control established under the Safe Drinking Water Act (SDWA), where such level or standard of control is applicable or relevant and appropriate to any hazardous substance, pollutant, or contaminant that will remain on-site. The enforceable standards under the SDWA are maximum contaminant levels (MCLs), which represent the maximum permissible level of a contaminant that is delivered to any user of a public water system. Because MCLs are usually only legally applicable under SDWA to the quality of drinking water at the tap, there will be few instances in which MCLs are applicable to cleanup of groundwater at a site. For this reason, MCLs are generally considered "relevant and appropriate" to groundwater that is or may be used for drinking.

Section 121(d) also states that remedial actions shall attain maximum contaminant level goals (MCLGs), where such goals are relevant and appropriate to the circumstances of the release. It is the EPA's opinion that for cases in which an MCLG establishes a contaminant level above zero, it is appropriate and consistent with CERCLA language to consider the MCLG as a potential relevant and appropriate requirement, and that determinations be made on a site-specific basis as to the relevance and appropriateness of meeting that level under the circumstances of the release (EPA 1990). When an MCLG is determined not to be relevant and appropriate to the circumstances of the release, the corresponding MCL will be considered a potential relevant and appropriate requirement and will be evaluated under the circumstances of the release. However, where an MCLG is equal to zero level of contaminants (as is the case for carcinogens such as trichloroethylene [TCE]), the MCLG is not "appropriate" for the cleanup of groundwater at CERCLA sites. In such cases, the corresponding MCL will be considered as a potential relevant and appropriate requirement.

Under the NCP, an alternate concentration limit (ACL) may be established in accordance with CERCLA Section 121(d)(2)(B)(ii). The EPA maintains that ACLs should be used only when active restoration of the groundwater to MCLs or nonzero MCLGs is not practicable. The availability

of institutional controls in itself is not sufficient reason to extend the allowance for levels above drinking water standards or nonzero goals; rather, institutional controls are considered the sole remedy only where active remediation is not practicable. It is EPA policy that if relevant and appropriate requirements (i.e., MCLs and MCLGs) exist for groundwater that is or may be used for drinking, a waiver is generally needed for cases in which they cannot be attained. However, if a situation fulfills the criteria for ACLs, including a finding that active restoration of the groundwater to MCLs or nonzero MCLGs is deemed to be impracticable, documentation of these conditions for the ACL is sufficient, and additional documentation of a waiver of the MCL or MCLG is not necessary.

The ACLs may be established where remediation of the groundwater is not practicable. EPA Directive 9283.1-2FS, "A Guide on Remedial Actions for Contaminated Ground Water," sets out factors that may cause active restoration to be impracticable or not cost effective, including:

- Widespread plumes, such as industrial areas, mining sites, and pesticide sites;
- Hydrogeological constraints, such as fractured bedrock or a transmissivity of less than 4.6 m^2/d (50 ft^2/d);
- Contaminant-related factors, such as the presence of dense, nonaqueous-phase liquids (DNAPLs); and
- Physical/chemical factors, such as partitioning to soil or organic matter.

However, CERCLA 121(d)(20)(B)(ii) restricts the use of ACLs to groundwater that discharges to nearby surface water and causes no statistically significant increase in contaminants in the surface water. In addition, provision must be made for enforceable institutional controls that prevent access to the contaminant plume.

Another provision of the preamble of the NCP states that the EPA agrees that meeting the conditions and requirements associated with a variance or exemption provision can be a means of compliance with an ARAR. Subpart B of 40 CFR Part 192 on "Standards for Cleanup of Land and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites" provides for ACLs if DOE has determined that the constituent will not pose a substantial present or potential hazard to human health and the environment as long as the ACL is not exceeded and the U.S. Nuclear Regulatory Commission has concurred (40 CFR 192.12). In considering the

present or potential hazard to human health and the environment of ACLs, the following factors shall be considered:

1. Potential adverse effects on groundwater quality, considering:

   (i) The physical and chemical characteristics of constituents in the residual radioactive material at the site, including their potential for migration;

   (ii) The hydrogeological characteristics of the site and surrounding land;

   (iii) The quantity of groundwater and the direction of groundwater flow;

   (iv) The proximity and withdrawal rates of groundwater users;

   (v) The current and future uses of groundwater in the region surrounding the site;

   (vi) The existing quality of groundwater, including other sources of contamination and their cumulative impact on the groundwater quality;

   (vii) The potential for health risks caused by human exposure to constituents;

   (viii) The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to constituents;

   (ix) The persistence and permanence of the potential adverse effects;

   (x) The presence of underground sources of drinking water and exempted aquifers identified under 40 CFR 144.7; and

2. Potential adverse effects on hydraulically connected surface water quality, considering:

   (i) The volume and physical and chemical characteristics of the residual radioactive material at the site;

   (ii) The hydrogeological characteristics of the site and surrounding land;

   (iii) The quantity and quality of groundwater, and the direction of groundwater flow;

   (iv) The patterns of rainfall in the region;

   (v) The proximity of the site to surface waters;

(vi) The current and future uses of surface waters in the region surrounding the site and any water quality standards established for those surface waters;

(vii) The existing quality of surface water, including other sources of contamination and their cumulative impact on surface water quality;

(viii) The potential for health risks caused by human exposure to constituents;

(ix) The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to constituents; and

(x) The persistence and permanence of the potential adverse effects.

Therefore, if after consideration of these factors, it appears that the criteria for establishing an ACL are met, the ACL is established as the ARAR.

In addition, these regulations for addressing contaminated groundwater at inactive uranium processing sites also provide for supplemental standards when one or more of the following criteria apply (40 CFR 192.21):

1. Remedial actions would pose a clear and present risk of injury to workers or to members of the public;
2. Remedial actions would, notwithstanding reasonable measures to limit damage, directly produce health and environmental harm that is clearly excessive compared to the health and environmental benefits, now or in the future;
3. The estimated cost at a "vicinity" site is unreasonably high relative to the long-term benefits, and the residual radioactive materials do not pose a clear present or future hazard;
4. There is no known remedial action;
5. The restoration of groundwater quality is technically impracticable from an engineering perspective; or
6. The groundwater is not a current or potential source of drinking water (based on concentrations of total dissolved solids; widespread, ambient

contamination; or the quantity of water reasonably available (40 CFR 192.11(e)).

If these criteria are met, a supplemental standard established in accordance with the regulation (40 CFR 192.22) would become the ARAR.

The point of compliance for groundwater cleanup standards is at appropriate locations in the groundwater (40 CFR 300.430(f)(5)(iii)(A)). The EPA believes that remediation levels should generally be attained either throughout the contaminated plume or at and beyond the edge of the waste management area where the waste is left in place. However, the EPA acknowledges that an alternative point of compliance may also be protective of human health and the environment under site-specific circumstances. In determining where to draw the point of compliance in such situations, the lead agency will consider factors such as proximity of the sources, technical practicability of groundwater remediation at that specific site, vulnerability of the groundwater and its possible uses, exposure and likelihood of exposure, and similar considerations.

Under the NCP, ARARs must be met during the course of the remedial action (40 CFR 300.435(b)(2)). However, in the preamble to the NCP, the EPA clarified that it recognized that ARARs used to determine final remediation levels (e.g., MCLs for groundwater remediation) apply only at the completion of the action (EPA 1990, p. 8755). In addition, CERCLA provides a waiver from ARARs for interim actions, provided the final action will attain the waived standard. If there is doubt about whether an ARAR represents a final remediation goal or an interim standard, and the ARAR cannot be met during the activity, this waiver could be invoked (EPA 1990). Groundwater ARARs for the alternatives analyzed in detail in this FS are final remediation levels and should have to be met only at the completion of the remediation period.

An alternative that does not meet an ARAR under federal environmental or state environmental or facility siting laws may be selected under five waiver circumstances (40 CFR 300.430(f)(1)(ii)(C)). (A sixth waiver is available to Superfund-financed sites, which would not be applicable to the WSCP and the WSOW.) These five relevant waiver circumstances are as follows:

1. The alternative is an interim measure and will become part of a total remedial action that will attain the ARAR;

2. Compliance with the requirement will result in greater risk to human health and the environment than other alternatives;
3. Compliance with the requirement is technically impracticable from an engineering perspective;
4. The alternative will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, or limitation through use of another method or approach; or
5. With respect to a state requirement, the state has not consistently applied, or demonstrated the intention to consistently apply, the promulgated requirement in similar circumstances at other remedial actions within the state.

The interim measure waiver requires that (1) the interim measure should be followed within a reasonable time by complete measures that will attain ARARs, and (2) the interim measure should not exacerbate site problems nor interfere with the final remedy. In the preamble to the NCP, the EPA, in response to comments, declined setting a specific time limit as a precondition for invoking this waiver because it is difficult to predict exactly when complete measures can be undertaken, given changes in funding, priorities, and other factors. The EPA believes that careful risk assessments may be used to show that greater risks will result from compliance with ARARs and that a waiver may be appropriate. However, the alternative to which compliance with an ARAR is compared is not limited to a "no action" alternative, but may be a less active measure (e.g., excavation vs. capping).

To obtain a waiver for technical impracticability, the EPA believes that criteria may include engineering feasibility and reliability; cost would generally not be a major factor unless compliance would be inordinately costly. The EPA believes that cost should generally play a subordinate role in determining practicability from an engineering perspective and states that "engineering practice is in reality ultimately limited by costs, hence cost may legitimately be considered in determining what is ultimately practicable" (EPA 1990, p. 8748). The proposed criteria for waiving an ARAR in lieu of an equivalent standard of performance include degree of protection, level of performance, reliability into the future, and time required for results. In the preamble to the final NCP, the EPA states that the first three criteria should be at least equal for an alternative to be considered

equivalent. In addition, the time required to achieve results using the alternative remedy should not be significantly more than that required under the waived ARAR. The EPA states that the fourth criterion proposed "was not specific precisely in order to allow cases where alternative methods may provide great benefits even though requiring longer time for implementation, as with, for example, the use of bioremediation instead of incineration" (EPA 1990, p. 8749). The last waiver is intended simply to prevent application of state requirements to Superfund sites that have not been consistently applied elsewhere in the state.

A.2 PRELIMINARY EVALUATION OF REQUIREMENTS

Requirements of federal and state laws that might be considered applicable or relevant and appropriate to the proposed remedial alternatives considered for detailed analysis in this FS are listed in Table A.1. Also included are potential TBC requirements and certain requirements that are part of employee protection laws or other nonenvironmental laws with which the CERCLA actions may have to comply and which are, therefore, not subject to the ARAR evaluation process for attainment or waiver. These requirements have simply been included as TBCs.

The preliminary ARAR and TBC determinations for these requirements are indicated in Table A.1. Because this appendix presents a comprehensive list of requirements, all determinations have been identified as "potentially" applicable, relevant and appropriate, or to-be-considered. These determinations will be finalized in consultation with the State of Missouri and EPA Region VII before the selected remedial action is implemented. During the finalization process, the requirements identified as potentially applicable will be reviewed to confirm direct applicability; only one requirement will be finalized from among those that regulate the same conditions or media. For those requirements identified as potentially relevant and appropriate, the specific portions of the requirement that have bearing on the action and the manner in which compliance would be achieved or waivers sought, will be finalized.

A.3 REFERENCES FOR APPENDIX A

U.S. Environmental Protection Agency, 1988, *Limiting Values of Radionuclide Intake and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, Federal Guidance Report No. 11, EPA-520/1-88-020, Office of Radiation Programs, Washington, D.C., Sept.

U.S. Environmental Protection Agency, 1990, "National Oil and Hazardous Substances Pollution Contingency Plan; Final Rule (40 CFR Part 300)," *Federal Register* 55(46):8666-8865, March 8.

U.S. Environmental Protection Agency, 1995, letter from C.M. Browner (U.S. Environmental Protection Agency, Washington, D.C.) to D.A. Shorr (Director, Missouri Department of Natural Resources, Jefferson City, Mo.), Nov. 1.

TABLE A.1 Groundwater Operable Unit ARARs

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Groundwater Standards for Remedial Actions at Inactive Uranium Processing Sites (40 CFR Part 192)	Uranium	Concentration limits in groundwater must not exceed the background level of that constituent in the groundwater or 30 pCi/L for uranium-234 and uranium-238 combined (where there is secular equilibrium, this criterion is satisfied by a concentration of 0.044 mg/L; for conditions of other than secular equilibrium, a corresponding value may be derived on the basis of the measured site-specific ratio of the two isotopes of uranium); or an alternative concentration limit set by the U.S. Nuclear Regulatory Commission, which has determined that the constituent will not pose a substantial current or potential future hazard to human health and the environment, on the basis of potential adverse effects on groundwater quality and potential adverse effects on hydraulically connected surface water quality.	Potentially relevant but not appropriate	This regulation is not applicable because the WSCP and WSOW are not inactive uranium processing sites regulated under 40 CFR Part 192. However, because no MCL or MCLG exists for uranium under the Safe Drinking Water Act, this regulation is potentially relevant to the cleanup levels proposed for groundwater. However, this standard was developed for sites generally located in arid regions of the western United States where water is a scarce resource. As such, this standard is not considered to be well suited to conditions at the WSCP and WSOW.
Safe Drinking Water Act; National Primary Drinking Water Regulations; Maximum Contaminant Levels (40 CFR 141.11 and 141.62); Missouri Drinking Water Regulations, Maximum Inorganic Chemical and Volatile Organic Contaminant Levels (10 CSR 60-4.030 and 60-4.100)	Organic and inorganic contaminants	The MCL is 0.005 mg/L for TCE. The MCL is 10 mg/L for nitrate-N.	Potentially relevant and appropriate	These regulations are not applicable because MCLs are applicable only to drinking water at the tap, not to groundwater. However, under the NCP, MCLs are relevant and appropriate to groundwater that is a potential drinking water source.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Safe Drinking Water Act, Proposed National Primary Drinking Water Regulations (40 CFR Part 141; 56 FR 33050 [July 18, 1991])	Radionuclides	The MCL for uranium in drinking water is 20 µg/L (20 µg/L is approximately equal to 14 pCi/L, for conditions of secular equilibrium between uranium-238 and uranium-234, which is applicable to groundwater conditions in the WSCP and the WSOW).	Potential TBC	Because this is a proposed regulation, it cannot be applicable or relevant and appropriate; however, it may be considered in developing a remediation level for uranium.
Radiation Protection of the Public and the Environment (DOE Order 5400.5)	Radionuclides	DOE Order 5400.5 establishes a maximum limit for the annual dose to members of the public of 100 mrem (1 mSv) total effective dose equivalent per year. All radiation exposures should be reduced to levels as low as reasonably achievable (ALARA). The derived concentration guide (DCG) values that would result in 100 mrem/yr for ingested water contaminated with uranium are as follows:	Potential TBC	Because DOE Orders are internal standards and requirements for the operation of DOE facilities, they are not ARARs; however, they may be considered in developing a remediation level for uranium.

Radionuclide[a]	DCG Values
Uranium 234	
f_1 value = 0.05	5×10^{-7}
f_1 value = 0.002	5×10^{-6}
Uranium 238	
f_1 value = 0.05	6×10^{-7}
f_1 value = 0.002	6×10^{-6}

[a] f_1 represents the fractional uptake from the small intestine to blood.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Drinking Water Regulations and Health Advisories (EPA 822-R-93-001, Office of Water, May 1995)	Nitroaromatic compounds and uranium	Health advisory (reference dose [RfD]) and drinking water equivalent levels (DWELs) for a 70-kg adult have been set as follows:	Potential TBC	These values are not regulations but may be used in the absence of regulatory limits for developing groundwater remediation levels.

	Long Term (mg/L)	RfD (mg/kg-d)	DWEL (mg/L)	Lifetime (mg/L)	mg/L at 10^{-4} Cancer Risk
2,4-DNT	1	0.002	0.1	NA[a]	0.005
2,6-DNT	1	0.001	0.04	NA	0.005
TNT	0.02	0.0005	0.02	0.002	0.1
Uranium	NA	0.003	NA	NA	NA

[a] NA = not applicable.

Missouri Water Quality Standards [10 CSR 20-7.031(5) and Table A]	Groundwater contaminants	Water contaminants shall not cause or contribute to exceedance of the following levels in aquifers. These criteria apply in any part of the aquifer, including the point at which the pollutant enters the aquifer. Where potential uses are not impaired, alternative site-specific criteria may be allowed. Those values listed as health advisory levels (as indicated below by an asterisk [*]) shall be used in establishing groundwater cleanup criteria until additional data become available to support alternative criteria or other standards are established.	Potentially applicable	These water quality standards apply to groundwater of the state, including establishing groundwater cleanup criteria.

Contaminant	Limits
Nitrobenzene	17 µg/L
2,4-Dinitrotoluene	0.11 µg/L
1,3-Dinitrobenzene	1.0 µg/L*

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.040); Maximum Permissible Exposure Limits	Radiation	For persons outside a controlled area, the maximum permissible whole-body doses due to sources in or migrating from the controlled area are limited to 2 mrem in any 1 hour, 0.1 rem in any 7 consecutive days, and 0.5 rem in any 1 year. (Note: a controlled area is an area that requires control of access, occupancy, and working conditions for radiation protection purposes; 0.5 rem = 500 mrem.)	Potential TBC	These requirements are part of an employee protection law (rather than an environmental law) and, therefore cannot be ARARs. However, they may provide guidance in determining a remediation level for uncontrolled areas.
Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR Part 192), Subpart D, Standards for Management of Uranium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as amended; Subpart E, Standards for Management of Thorium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as amended.	Radiation	Processing operations during and prior to the end of the closure period at a facility managing uranium and thorium by-product materials should be conducted in a manner than provides reasonable assurance that the annual dose equivalent does not exceed 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ of any member of the public as a result of exposures to the planned discharge of radioactive material to the general environment (excluding radon-222, radon-220, and their decay products).	Potentially relevant and appropriate	These requirements would not be applicable because the remedial action does not constitute a processing operation, nor does it include a planned discharge of radioactive material to the environment. Nevertheless, the requirements could be considered relevant and appropriate to protection of the public during implementation of an action that generates radioactive waste (i.e., soils) because the waste type and the potential release issue could be considered sufficiently similar.
Radiation Protection of the Public and the Environment (DOE Order 5400.5)	Radiation	The concentration of radionuclides in liquid wastes discharged to natural waterways should be reduced to levels ensuring that the absorbed dose to native aquatic animal organisms does not exceed 1 rad/d.	To be considered	If water treatment is part of the selected remedy, this requirement, although not a promulgated standard, provides protection for aquatic organisms from liquid discharges with which the remedial action would comply.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Resource Conservation and Recovery Act (RCRA) (40 CFR 262.11)	Investigative-derived waste	All waste generated from well construction must be characterized; if it is hazardous waste under RCRA, it must be managed and disposed of properly.	Potentially applicable	Investigative-derived waste may be placed in an on-site disposal facility or may be transported to an off-site facility that is in compliance with RCRA.
Missouri Construction and Operating Permit Regulations (10 CSR 20-6.010)	Wastewater discharge	A wastewater treatment plant must be constructed and operated in accordance with a state-approved engineering report and detailed plans and specifications so as to meet the state-specified contaminant release concentrations and/or weights in compliance with the Missouri Clean Water Law.	Potentially applicable	If water treatment is part of the selected remedy, pursuant to CERCLA §121(e), no permit is required for on-site activities; however, substantive permit conditions such as construction, engineering, and operating requirements for the treatment facility would be applicable to any wastewater treatment facility constructed on-site, or in very close proximity to the contamination, as part of a remedial action. If the wastewater is to be treated in the existing on-site treatment plant, and the discharge would violate existing effluent limitations in place for the plant, modification of the existing operation or discharge conditions may be necessary.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Missouri General Protection of Groundwater Quality and Resources (10 CSR 23-4.050)	Well construction	All monitoring wells must be constructed in accordance with the rules (10 CSR 23-4.060), and an annular space must be sealed. When no longer in service, monitoring wells must be properly plugged. New off-site monitoring wells must be constructed by licensed monitoring well diggers, pursuant to a well permit, and the construction must be reported to the Division for review by using a certification report form.	Potentially applicable	Pursuant to CERCLA §121(e), no permit is required for on-site well construction; however, substantive permit conditions for the construction of the wells would be applicable.
Missouri Stormwater Discharge Regulations [10 CSR 20-6.010(13)]	Stormwater discharges	Missouri has issued stormwater general permits for discharges associated with land disturbance activities. The general permits contain general conditions, effluent limitations, and a requirement for the development of Stormwater Pollution Prevention Plans to prevent construction site runoff from polluting surface waters of the state.	Potentially applicable	If the remedial action involves land disturbance activities, the substantive portions of the Missouri stormwater general permit would be applicable, unless the activities are exempted under the permit (i.e., insufficient acreage).
National Emission Standards for Hazardous Air Pollutants (40 CFR 61), Subpart H, National Emission Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities	Radionuclides other than radon-220 and radon-222	Emissions of such radionuclides to the ambient air from DOE facilities should not result in an effective dose equivalent of >10 mrem/yr to any member of the public.	Potentially relevant and appropriate	These requirements would only be applicable to protection of the public during implementation of the remedial action at a DOE facility that involved disturbance of radionuclide contaminated soil or material. Since the proposed remedial action is not on a DOE facility, these regulations may be relevant and appropriate.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Radiation Protection of the Public and the Environment (DOE Order 5400.5)	Specific radionuclides (see table)	Residual concentrations of radionuclides in air in uncontrolled areas are limited to the following: Derived Concentration Guides[a] (µCi/mL) Isotope / D / W / Y Uranium-235: 5×10^{-12} / 2×10^{-12} / 1×10^{-13} Uranium-238: 5×10^{-12} / 2×10^{-12} / 1×10^{-13} [a] D, W, and Y represent lung retention classes; removal half-times assigned to the compounds in classes D, W, and Y are 0.5, 50, and 500 days, respectively. Exposure conditions assume an inhalation rate of 8,400 m^3 of air per year (based on an exposure over 24 hours per day, 365 days per year). For known mixtures of radionuclides, the sum of the ratios of the observed concentration of each radionuclide to its corresponding limit should not exceed 1.0.	To be considered	Although not promulgated standards, these constitute requirements for protection of the public with which the remedial action that involved disturbance of radionuclide-contaminated soil or material would comply.
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.040), Maximum Permissible Exposure Limits	Specific radionuclides (see table)	The concentrations above natural background of radionuclides in air outside a controlled area, averaged over any calendar quarter, should not exceed the following limits: Concentration Limit (µCi/mL) Isotope / Soluble / Insoluble Uranium-235: 2×10^{-11} / 4×10^{-12} Uranium-238: 3×10^{-12} / 5×10^{-12}	Potentially applicable	These requirements would be applicable to protection of the public during implementation of a remedial action that involves disturbance of radionuclide-contaminated soil or material.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Missouri Air Pollution Control Regulations; Air Quality Standards and Air Pollution Control Regulations for the St. Louis Metropolitan Area (10 CSR 10-5.180), Emission of Visible Air Contaminants from Internal Combustion Engines	Particulate matter	Visible air contaminants (other than uncombined water) should not be released from an internal combustion engine for more than 10 seconds at any one time.	Potentially applicable	These requirements would be applicable to particulates released from any internal combustion engines used during the remedial action.
Missouri Air Quality Standards (10 CSR 10-6.170), Restriction of Particulate Matter to the Ambient Air Beyond the Premises of Origin	Particulate matter	No person should permit the handling, transport, or storage of any material without applying reasonable measures as may be required to prevent fugitive particulate matter from going beyond the premises of origin in quantities such that (1) the particulate matter remains visible in the ambient air beyond the property line of origin or (2) the particulate matter may be found on surfaces beyond the property line of origin. To prevent particulate matter from going beyond the premises of origin during construction, repair, cleaning, or demolition of a building or its appurtenances; construction or use of a road, driveway, or open area; or operation of a commercial or industrial installation, the following measures may be required: revision of procedures involving construction, repair, cleaning, and demolition of buildings that produce particulate matter emissions; paving or frequent cleaning of roads; application of dust-free surfaces or water; and planting and maintaining a vegetative ground cover.	Potentially applicable	These requirements would be applicable to releases of particulates from the listed activities during implementation of the remedial action.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Radioactive Waste Management (DOE Order 5820.2A)	Radioactive waste management	External exposure to radioactive waste (including releases) should not result in an effective dose equivalent of >25 mrem/yr to any member of the public, and releases to the atmosphere should meet the requirements of 40 CFR Part 61 (see discussion above). An environmental monitoring program should be implemented to address compliance with performance standards.	To be considered	Although not promulgated standards, these constitute requirements for controlling exposures and releases and for environmental monitoring with which the remedial action that involves the generation of radionuclide-contaminated wastes would comply.
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.070), Storage of Radioactive Materials	Radioactive waste storage	Radioactive materials should be stored in a manner that will not result in the exposure of any person, during routine access to a controlled area, in excess of the limits identified in 19 CSR 20-10.040 (see related discussion for contaminant-specific requirements); a facility used to store materials that may emit radioactive gases or airborne particulate matter should be vented to ensure that the concentration of such substances in air does not constitute a radiation hazard; and provisions should be made to minimize the hazard to emergency workers in the event of a fire, earthquake, flood, or windstorm.	Potentially applicable	These requirements would be applicable to the temporary storage of certain material that would be generated during the remedial action, pending the availability of a disposal facility.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.080), Control of Radioactive Contamination	Radioactive waste manage-ment	All work should be carried out under conditions that minimize the potential spread of radioactive material that could result in the exposure of any person above any limit specified in 19 CSR 20-10.040 (see related discussion for contaminant-specific requirements). Clothing and other personal contamination should be monitored and removed according to procedures established by a qualified expert; any material contaminated to the degree that a person could be exposed to radiation above any limit specified in 19 CSR 20-10.040 should be retained on-site until it can be decontaminated or disposed of according to procedures established by a qualified expert.	Not an ARAR	These requirements are part of an employee protection law (rather than an environmental law) with which CERCLA response actions should comply; hence, they are not subject to the ARAR process. However, they constitute requirements for worker protection with which the proposed action would comply.
Atomic Energy Act, as amended (42 USC 2112)	Radioactive waste disposal	The DOE can distribute by-product material only to individuals or organizations who are licensed by the NRC to receive such material.	Potentially applicable	These requirements would be applicable if the disposal of radioactively contaminated (by-product) material from the Weldon Spring site would take place at a commercial facility (e.g., the Envirocare site near Clive, Utah).
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.090), Disposal of Radioactive Wastes	Radioactive waste disposal	Radioactive waste material should not be disposed of by dumping or burial in soil, except at sites approved by and registered with the Missouri Department of Health; a permit should be obtained for holding and preparation of such material prior to disposal; and no releases to air or water should cause exposure to any person above the limits specified in 19 CSR 20-10.041 (see related discussion for contaminant-specific requirements).	Potentially applicable	If the remedial action involves radioactive waste from excavation or water treatment activities that would be disposed of at the on-site, approved cell or at a properly licensed off-site commercial disposal facility, these requirements may be applicable.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.040), Maximum Permissible Exposure Limits	Radiation	Limits for occupational doses from ionizing radiation in a controlled area are as follows:	Not an ARAR	These requirements are part of an employee protection law (rather than an environmental law) with which CERCLA response actions should comply; hence, they are not subject to the ARAR process. They are indicated in this table to identify requirements for worker protection with which the remedial action would comply.

Part of Body	Maximum Dose in Any Calendar Year (rem)	Maximum Dose in Any Calendar Quarter (rem)
Whole body, head and trunk, major portion of bone marrow, gonads, or lens of eye	5	3
Hands and fore-arms, feet and ankles	75	25
Skin of large body area	30	10

Also, the whole-body dose added to the cumulative occupational dose should not exceed 5(N-18) rem, where N is the age of the exposed individual.

Occupational exposure to airborne radioactive material, averaged over any calendar quarter, should not exceed the following limits:

	Concentration Limit (μCi/mL)	
Isotope	Soluble	Insoluble
Uranium-235	5×10^{-10}	1×10^{-10}
Uranium-238	7×10^{-11}	1×10^{-10}

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Missouri Radiation Regulations; Protection Against Ionizing Radiation (19 CSR 20-10.050), Personnel Monitoring and Radiation Surveys	Radiation	Personnel monitoring and radiation surveys are required for each worker for whom there is any reasonable possibility of receiving a weekly dose from all radiation exceeding 50 mrem, taking into consideration the use of protective gloves and radiation-limiting devices. An exemption from routine monitoring may be granted under certain conditions.	Not an ARAR	These requirements are part of an employee protection law (rather than an environmental law) with which CERCLA response actions should comply; hence, they are not subject to the ARAR process. They are indicated in this table to identify requirements for worker protection with which the remedial action would comply.
Occupational Safety and Health Administration Standards; Occupational Health and Environmental Control (29 CFR Part 1910; 1910.96), Subpart G, Ionizing Radiation	Radiation	The dose per calendar quarter resulting from exposure to radiation in a restricted area from sources in that area is limited to the following: Part of Body — Dose (rem) Whole body, head and trunk, active blood-forming organs, lens of eye, or gonads — 1.25 Hands and forearms, feet and ankles — 18.25 Skin of whole body — 7.5 The occupational exposure of an individual younger than 18 is restricted to 10% of these limits; the whole-body dose to a worker may not exceed 3 rem in a calendar quarter and, when added to the cumulative occupational dose, should not exceed 5(N – 8) rem, where N is the age of the exposed individual.	Not an ARAR	These requirements are part of an employee protection law (rather than an environmental law) with which CERCLA response actions should comply. Therefore, these requirements are not subject to the ARAR evaluation process for attainment or waiver. They are indicated in this table to identify requirements for worker protection with which the remedial action would comply.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
		Occupational exposure to airborne radioactive material should not exceed the following concentrations, averaged over a 40-hour workweek of seven consecutive days:		

Isotope	Concentration Limit (µCi/mL) Soluble	Insoluble
Uranium-235	5×10^{-10}	1×10^{-10}
Uranium-238	7×10^{-11}	1×10^{-10}

For mixtures of radionuclides, the sum of the ratios of the quantity present to the specific limit should not exceed 1. For uranium, chemical toxicity may be the limiting factor for soluble mixtures of uranium in air; if the percent by weight of uranium-235 is less than 5, the concentration limit for total uranium is 0.2 mg/m^3 of inhaled air. For hours of exposure less than or greater than 40, the limits are proportionately increased or decreased, respectively.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Occupational Radiation Protection (10 CFR Part 835)	Radionuclides	This regulation sets annual limits on intake (ALIs) for occupational exposure through ingestion during DOE activities. The oral ingestion ALIs are the annual intakes of a given radionuclide by "reference man" that would result in either a committed effective dose equivalent of 5 rem/yr (stochastic ALI) or a committed dose equivalent of 50 rem/yr to an organ or tissue (nonstochastic ALI). The ALIs are provided in Table 1 of EPA's Federal Guidance Report No. 11, *Limiting Values of Radionuclide Intake and Dose Conversion Factors for Inhalation, Submersion, and Ingestion* (September 1988). The ingestion ALIs for uranium-234 and uranium-238 are provided below. The critical organ for the nonstochastic dose is the bone surface.	Not an ARAR	These requirements are part of an employee protection law (rather than an environmental law) and, therefore, cannot be ARARs. However, they may be considered in performing remediation activities.

Radionuclide[a]	ALI (µCi) Stochastic (5 rem/yr)	ALI (µCi) Nonstochastic (50 rem/yr)
Uranium-234		
f_1 value = 0.05	NA[b]	10
f_1 value = 0.002	200	NA
Uranium-238		
f_1 value = 0.05	NA	10
f_1 value = 0.002	200	NA

[a] f_1 represents the fractional uptake from the small intestine to blood.

[b] NA = not applicable.

TABLE A.1 (Cont.)

Citation	Contaminant/ Activity	Requirement	Preliminary Determination	Remarks
Occupational Safety and Health Administration Standards (29 CFR 1910; 1910.1000), Subpart Z, Toxic and Hazardous Substances	Specific organic and inorganic substances	Permissible occupational exposure limits for various airborne substances have recently been revised to the following final rule limits; they may be achieved by any reasonable combination of engineering controls, work practices, and personal protective equipment:	Not an ARAR	These requirements are part of an employee protection law (rather than an environmental law) with which CERCLA response actions should comply; hence, they are not subject to the ARAR process. They are indicated in this table to identify requirements for worker protection with which the remedial action would comply.

Parameter[a]	Limit[b] (mg/m^3)	Condition
Uranium	0.05	For soluble compounds, as uranium; limit for insoluble compounds, as uranium, is 0.2 mg/m^3, with a short-term (15-min) exposure limit of 0.6 mg/m^3.
DNB	1	For all DNB isomers.[c]
2,4-DNT	1.5	For total DNT; isomer unspecified.[c]
2,6-DNT	1.5	For total DNT; isomer unspecified.[c]
NB	5	See footnote c.
TNB	0.5	See footnote c.
TNT	0.5	See footnote c.

[a] Notation: DNB, dinitrobenzene; 2,4-DNT, 2,4-dinitrotoluene; 2,6-DNT, 2,6-dinitrotoluene; NB, nitrobenzene; TNB, trinitrobenzene; TNT, trinitrotoluene.

[b] Permissible exposure limit (PEL) expressed as the 8-hour time-weighted average, except as noted.

[c] Skin absorption to be reduced (e.g., with protective clothing) to limit overall exposure via the cutaneous route (airborne or direct contact).

APPENDIX B:

DERIVATION OF RISK-BASED PRELIMINARY REMEDIATION GOALS FOR GROUNDWATER AT THE WSCP AND THE WSOW

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Preliminary remediation goals (PRGs) for trichloroethylene (TCE), nitrate, nitroaromatic compounds (i.e., 2,4,6-trinitrotoluene [2,4,6-TNT], 2,4-dinitrotoluene [2,4-DNT], 2,6-DNT, 2-amino-4,6-DNT, 4-amino-2,6-DNT, 1,3,5-trinitrobenzene [1,3,5-TNB], 1,3-dinitrobenzene [1,3-DNB], nitrotoluenes, and nitrobenzene), and uranium are identified in this Feasibility Study (FS) as a basis for evaluating the effectiveness of the various technologies and alternatives being considered. The risk-based PRGs are calculated concentrations of contaminants in groundwater that correspond to different levels of risk and hazard quotients. These risk-based concentrations were derived for each contaminant of concern (COC) on the basis of the methodology and assumptions used in the Baseline Risk Assessment ([BRA]; U.S. Department of Energy [DOE] and U.S. Department of the Army [DA] 1998). Concentrations of carcinogenic contaminants equivalent to the 1×10^{-4} and 1×10^{-6} risk range for the recreational and residential scenarios were estimated to provide a range of information for risk management purposes. Calculations were also performed to determine the concentrations of noncarcinogenic contaminants that would be equivalent to a hazard index of 1 for both scenarios.

The primary pathway of exposure for both scenarios is ingestion. The exposure parameters used in the calculations are provided in Table B.1. The range of concentrations calculated for each contaminant and scenario are presented in Table B.2.

Concentrations of uranium in groundwater (in pCi/L) corresponding to a specified risk level were calculated as follows:

$$R_{wi} = TR / IR \times EF \times ED \times Sf_{ing} , \qquad \text{(B.1)}$$

where:

R_{wi} = concentration of radionuclide in water (pCi/L),

TR = target excess individual lifetime cancer risk (unitless),

IR = water ingestion rate (L/d),

TABLE B.1 Exposure Scenario Assumptions and Intake Parameters

Parameter	Unit	Current or Future Recreational Visitor	Hypothetical Future Resident
Exposure frequency	events/yr	20	350
Exposure duration	yr	30	30
Body weight	kg	70	70
Spring water ingestion rate	mL/event	400	NA[a]
Groundwater ingestion rate	L/event	NA	2

[a] NA = not applicable.

TABLE B.2 Water Concentrations of COCs Associated with the Acceptable Risk Range and Hazard Index

	Concentration (µg/L unless otherwise indicated)			
	Residential Scenario		Recreational Scenario	
Contaminant of Concern	10^{-6} to 10^{-4} Carcinogenic Risk Range	Hazard Index of 1	10^{-6} to 10^{-4} Carcinogenic Risk Range	Hazard Index of 1
TCE	7.7-770	NA[a]	680-68,000	NA
Nitrate-N	NA	58	NA	5,100
2,4,6-TNT	2.8-280	18	250-25,000	1,600
2,4-DNT	0.13-13	73	11-1,100	6,400
2,6-DNT	0.13-13	37	11-1,100	3,200
2-Amino-4,6-DNT	NA	2.2	NA	190
4-Amino-2,6-DNT	NA	2.2	NA	190
1,3,5-TNB	NA	1.8	NA	160
1,3-DNB	NA	3.7	NA	320
m-Nitrotoluene	NA	37	NA	3,200
o-Nitrotoluene	NA	37	NA	3,200
p-Nitrotoluene	NA	37	NA	3,200
Nitrobenzene	NA	18	NA	1,600
Uranium	0.90–90 pCi/L	110[b]	78–7,800 pCi/L	9,600[c]

[a] NA = not applicable.

[b] Based on radiological risk for uranium.

[c] Based on chemical toxicity of uranium.

EF = exposure frequency (d/yr),

ED = exposure duration (yr), and

Sf_{ing} = ingestion slope factor for uranium (5.3×10^{-11} / pCi).

For the chemical contaminants, the concentration corresponding to specified risk levels was calculated as follows:

$$C_{wi} = TR \times BW \times AT \times CF / Sf_{oi} \times IR \times EF \times ED, \quad \text{(B.2)}$$

where:

C_{wi} = concentration of contaminant in water (ug/L),

BW = average body weight over the exposure period (kg),

AT = averaging time (d),

CF = conversion factor (10^3 µg/mg), and

Sf_{oi} = oral slope factor for contaminant i ([mg/kg-d]$^{-1}$, see Table 4.2 of the BRA [DOE and DA 1998]).

The concentrations corresponding to specified hazard quotients were calculated as follows:

$$C_{wi} = THI \times BW \times AT \times CF \times RfD_{oi} / IR \times EF \times ED, \quad \text{(B.3)}$$

where:

THI = target hazard index (unitless), and

RfD_{oi} = oral reference dose for contaminant i (mg/kg-d, see Table 4.1 of the BRA [DOE and DA 1998]).

REFERENCE FOR APPENDIX B

U.S. Department of Energy and U.S. Department of the Army, 1998, *Baseline Risk Assessment for the Groundwater Operable Units at the Chemical Plant Area and the Ordnance Works Area, Weldon Spring, Missouri*, DOE/OR/21548-568, Draft Final, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Department of Energy, Weldon Spring Site Remedial Action Project, Weldon Spring, Mo., and U.S. Department of the Army, Corps of Engineers, Kansas City District, Kansas City, Mo., Feb.

APPENDIX C:

METHODOLOGY AND ASSUMPTIONS USED TO CALCULATE THE POTENTIAL NUMBER OF EXTRACTION WELLS FOR THE WSCP AND THE WSOW

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METHODOLOGY AND ASSUMPTIONS USED TO CALCULATE THE POTENTIAL NUMBER OF EXTRACTION WELLS FOR THE WSCP AND THE WSOW

The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation of potential alternatives for addressing groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively, in St. Charles County, Missouri. This appendix discusses the methodology and assumptions used to calculate the number of extraction wells required to support Alternatives 3, 4, and 5. The number of wells required serves as input in selecting the best strategy for site remediation.

C.1 METHODOLOGY

As a rule, more extraction wells promote faster site cleanup. Because of costs, however, large numbers of extraction wells are not feasible. The minimum number of wells that can be used to effect site remediation for a confined groundwater aquifer (assuming that further site contamination is undesirable) can be estimated by using the method presented by Javandel and Tsang (1986). (The Javandel/Tsang method is the basis of the two-dimensional model RESSQ, a computer code used to evaluate cleanup schemes that use extraction wells for plume capture [Javandel et al. 1984].) In this method, a number of colinear extraction wells, n, are installed perpendicular to the direction of groundwater flow near the leading edge of a contaminant plume or in a direction downstream of a local "hot spot." These wells will form a capture zone that can be defined by complex potential theory (Milne-Thomson 1968) as the dividing stream line given by the expression

$$y = \pm \frac{nQ}{2BU} - \pm \frac{Q}{2\pi BU} \sum_{1}^{n} \tan^{-1} \frac{y - y_i}{x} , \qquad \text{(C.1)}$$

where B is the thickness of the aquifer, Q is the volumetric rate of extraction, U is the Darcy velocity, and x and y are the coordinates of the stream line. The Darcy velocity, U, is simply given as

$$U = - K\nabla h , \qquad \text{(C.2)}$$

where K is the hydraulic conductivity of the porous medium and ∇h is the hydraulic gradient (Freeze and Cherry 1979).

By orienting the coordinate system of the wells such that the wells lie symmetrically along the y-axis ($x = 0$), Equation C.1 can be simplified to the following result if each well is pumped at the same rate:

$$y = \pm \frac{nQ}{4BU} . \tag{C.3}$$

For a large n, the approximate spacing between adjacent wells, s, is given by the expression:

$$s = \frac{1.2Q}{\pi BU} . \tag{C.4}$$

For a contaminant plume having a full width, W, capture can be conservatively achieved by setting y to $W/2$. For this condition, the number of wells required is given by the expression

$$n = \frac{2B\nabla hKW}{Q} . \tag{C.5}$$

Equations C.4 and C.5 are usually solved iteratively (Javandel and Tsang 1986) to determine the number of wells that, for given pump rates and aquifer properties, produce a drawdown that will capture the contaminant plume laterally and vertically. As expressed here, Equations C.4 and C.5 indicate that the aquifer is treated as being homogeneous and isotropic. In addition, the hydraulic gradient was assumed to be constant across the width of the plume. Because these conditions are unlikely to be met at the WSOW or WSCP, use of the Javandel/Tsang method will produce approximate results. By judiciously selecting the system parameters, a conservative estimate of the number of extractions wells required can be calculated.

If the groundwater aquifer is unconfined, Equation C.5 can be replaced with the expression

$$n = \frac{WK\left(\frac{h_1^2 - h_2^2}{L}\right)}{Q} , \tag{C.6}$$

where h_1 and h_2 are the potentiometric heads of the aquifer at locations 1 and 2 that are separated by a distance L in a direction parallel to the natural flow direction (Grubb 1993). As shown by Grubb (1993), stagnation points and dividing stream lines for the unconfined case are slightly less than their

corresponding values for confined conditions (less than about 10% for the example problem shown), and the number of extraction wells required to capture a plume having a width W is slightly greater. Because information on the minimum number of extraction wells is desired for the present set of calculations, and because it is difficult to define the required potentiometric heads and separation distances in Equation C.6, the calculations were performed on the basis of the assumption that the aquifer behaves as if it were under confined conditions. The error introduced by this assumption is expected to be small and within the uncertainties of the other associated parameters.

C.2 CALCULATIONS FOR THE NUMBER OF EXTRACTION WELLS

Two methods were used to estimate the minimum number of extraction wells needed to remediate contaminated groundwater at the WSCP and the WSOW. In the first method, sitewide values for hydraulic conductivity and other relevant parameters were used to provide rough estimates of the total number of extraction wells needed. No attempt was made to evaluate the uncertainty associated with these estimates. In the second method, the number of extraction wells required and their uncertainties were estimated on the basis of conditions most applicable to the regions of contamination. These calculations were performed for areas in which the maximum concentrations for post-1995 data exceeded the applicable or relevant and appropriate requirements (ARARs) for the contaminants of concern (COCs) (Table 1.3 in this feasibility study [FS]). Values predicted by using this second method provide more realistic estimates of the number of wells required. Both methods for calculating the number of extraction wells required are discussed below.

C.2.1 Estimating the Number of Extraction Wells on the Basis of Sitewide Hydraulic Conductivity Values

To apply Equation C.5, the following site parameters are required:

- Volumetric extraction rate for the wells,
- Hydraulic gradient,
- Hydraulic conductivity,
- Aquifer thickness, and
- Width of the plume.

The following sections discuss each of the above parameters for the WSCP and the WSOW.

C.2.1.1 Volumetric Extraction Rate

Little site-specific information is available on the sustainable pumping rates for either the WSCP or the WSOW. Aquifer tests (i.e., three pumping tests) conducted by the program management contractor indicate that the maximum sustainable pumping rate is about 0.3 gallon per minute (gpm) at the WSCP (MK-Ferguson Company and Jacobs Engineering Group, Inc. 1990). Two of the three pump tests were conducted near areas identified as having discrete flow. In other locations, the sustainable pumping rates might be lower, especially if the well intercepts a more unweathered portion of the limestone aquifer. Use of the known value (0.3 gpm) in Equations C.4 and C.5 will produce a conservative estimate of the number of extraction wells required (i.e., the estimated number will be greater than the actual number required). Sustainable pumping rates for the WSOW are not known; however, because of the similarity in hydrogeology, the rates are probably similar to those for the WSCP.

The Javandel/Tsang method (Javandel and Tsang 1986) is usually performed iteratively (see Section C.1). Because aquifer properties, sustainable pumping rates, local hydraulic gradients, and the vertical and lateral extent of contaminant plumes at the WSOW and WSCP are not accurately known, a single pumping rate (0.3 gpm) was assigned for all of the calculations, and no iteration was performed. This pumping rate was then assumed to produce sufficient drawdown to contain the plume of interest. Although such a simplification introduces some uncertainty into the calculations, the results are expected to be conservative (i.e., the number of wells calculated will be smaller than the actual number required) and useful for the scoping analyses of this FS.

C.2.1.2 Hydraulic Gradient

The hydraulic gradient north of the groundwater divide at the WSCP and WSOW is about 0.01 ft/ft; south of the divide, the gradient is higher, about 0.04 ft/ft, consistent with the steeper topography in this region (DOE and DA 1997). Although the value of the gradient changes on a local scale, these two values were used in Equations C.4 and C.6 to provide approximate results for the number of extraction wells required.

C.2.1.3 Width of Contaminated Groundwater

By definition, the width of a contaminant groundwater plume is a function of the concentration used to define its boundary. This concentration, in turn, also depends on the scenario being evaluated and the methods being used to establish concentration limits (e.g., risk-based analyses). For the current calculations, the boundaries of the contaminant plumes were defined by concentration limits calculated for the recreational scenario.

No defined plumes occur within the WSOW. Rather, there are a total of four "hot spots" at well locations MWV-9, MWS-12, MWS-17, and MWS-21. For these calculations, a capture-zone width of 488 m (1,600 ft) was used. The lines of wells were oriented perpendicular to the assumed direction of groundwater flow.

Similar to the situation at the WSOW, no well-defined plumes occur at the WSCP, but 10 hot spots are present, again on the basis of the recreational scenario. Like those at the WSOW, some of the hot spots at the WSCP were defined by one contaminated well; others were defined by several contaminated wells in a cluster. For each hot spot, a capture line was assumed. The lengths of these lines were variable (Table C.1) and based on the lateral extent of contamination and the type of contaminant present (full width of the capture zone based on the widest contaminated zone present). As they were for the WSOW, the capture lines of wells at the WSCP were oriented in a direction perpendicular to the assumed direction of groundwater flow.

C.2.1.4 Hydraulic Conductivity

Two values of hydraulic conductivity were used in the calculations (Table C.1). A value of 0.28 ft/d (0.0001 cm/s) was used for the WSOW, consistent with reported values within the Burlington-Keokuk Formation. For the WSCP, a value of 0.28 ft/d (0.0001 cm/s) was used in regions south of the groundwater divide; a value 10 times larger (2.8 ft/d [0.001 cm/s]) was used for regions north of the divide on the basis of the results of slug test data. These values are consistent with measured values within the WSCP (DOE and DA 1997).

TABLE C.1 Input Parameters and Calculated Number of Extraction Wells for Each of the Contaminated Areas at the WSOW and WSCP

Well/Area	Input Parameters: Groundwater (ft)	Gradient (ft/ft)	Hydraulic Conductivity (ft/d)	Thickness of Contaminated Aquifer (ft)	Calculated Number of Extraction Wells: Number	Total
WSOW						
Individual wells						
MWS-9	1,600	0.01	0.28	22	3	
MWS-12	1,600	0.01	0.28	26	4	
MWV-17	1,600	0.01	0.28	33	5	WSOW = 12
WSCP						
Individual wells						
MW-2030	500	0.01	2.8	30	14	
MW-2032	500	0.01	2.8	10	5	
MW-3024	250	0.01	2.8	48	12	
MW-4013	500	0.01	2.8	25	12	
MW-4024	500	0.04	0.28	35	7	
MWS-21[a,b]	1,600	0.01	0.28	15	2	
	1,600	0.04	0.28	15	9	
Well clusters						
MW-2037 MW-3012 MW-3026 MW-3027 MW-4001	1,000	0.01	2.8	64	62	
MW-2001 MW-2002 MW-2003 MW-2005 MW-3003 MW-3023 MW-4011	1,850	0.01	2.8	62	111	
MW-2038 MW-2040[b]	1,900	0.01	0.28	30	6	
MW-2039 MW-2040[b] MW-2041	1,200	0.04	0.28	39	18	WSCP = 258

[a] The contaminants detected in WSOW well MWS-21 are associated with the WSCP; this well is included with the WSCP contaminated wells.

[b] WSOW well MWS-21 and WSCP well MW-2040 are located near the groundwater divide. The number of extraction wells was calculated by assuming that contaminants could potentially migrate north and south of the divide.

C.2.1.5 Aquifer Thickness

The approximate thickness of the contaminated aquifer in the vicinity of the capture lines was assigned on the basis of published data (Mugel 1997); these values are listed in Table C.1. The thickness of the contaminated aquifer was assumed to be equal to the difference between the water table and the depth of the bottom of the screened interval that was showing contamination, except for well MW-3024. It is a deep, unweathered well clustered with well MW-3025. For MW-3024, the thickness of the contaminated aquifer was assumed to be equal to the difference between the bottom of MW-3025 (a clean well) and the bottom of the screened interval of MW-3024. If a particular hot spot was defined by more than one well, the well with the larger value (i.e., largest thickness) was used in the calculation. In this way, conservative estimates for the number of wells would be obtained.

C.2.1.6 Results

Information on the number of wells required for each line at the WSOW and WSCP is summarized in Table C.1. At the WSOW, approximately 12 wells would be required to contain and capture contaminated material in the vicinity of the hot spots; at the WSCP, about 258 wells would be required.

C.2.2 Estimating the Number of Extraction Wells and Associated Uncertainties on the Basis of Local Conditions

As discussed above, Equation C.5 was used to estimate the minimum number of extraction wells, n, required to prevent further downstream contamination and to clean up contaminated zones associated with the wells that have maximum post-1995 contaminant concentrations that exceed their respective preliminary remediation goals (PRGs) (Table 1.3 in this FS). In some cases, contamination appears to localized in an individual well in which one or more COCs exceed their PRGs. In other cases, a number of wells appear to share a common contaminated area that contains one or more contaminants. Tables C.2 and C.3 list the individual wells that have concentrations that exceed their respective PRGs and wells that span the same contaminated zone. As indicated in these tables, the WSCP has four zones of contamination and four individual wells. The WSOW, on the

TABLE C.2 Wells Associated with Zones of Contamination at the WSCP

Contaminated Zone	Well	Contaminant[a]
1	MW-2037	TCE
	MW-2038	TCE
	MW-3025	TCE
	MWS-21	TCE
	MW-2036	-
	MW-2039	Nitrate, 2,4-DNT
	MW-4004	-
2	MW-4001	Nitrate, 2,4-DNT
	MW-3027	Nitrate
3	MW-2001	Nitrate, 2,4-DNT
	MW-2002	Nitrate
	MW-2003	Nitrate, 2,4-DNT
	MW-2005	Nitrate
	MW-3023	Nitrate, 2,4-DNT
4	MW-2006	2,4-DNT
	MW-2011	2,4-DNT
	MW-2013	2,4-DNT
	MW-2014	2,4-DNT
5	MW-4013	Nitrate
6	MW-2032	Nitrate, 2,4-DNT
7	MW-4015	2,4-DNT
8	MW-4002	2,4-DNT

[a] TCE = trichloroethylene, DNT = dinitrotoluene, and a hyphen indicates that contaminant concentrations are below their respective preliminary remediation goals.

TABLE C.3 Wells Associated with Zones of Contamination at the WSOW

Contaminated Zone	Well	Contaminant[a]
1	MWS-12	2,4-DNT, 2,6-DNT
2	MWS-17	2,4-DNT, 2,6-DNT
3	MWS-21	TCE, nitrate, 2,4-DNT (also in WSCP zone 1)
4	MWV-9	2,4-DNT
	MWV-24	2,4-DNT
5	MW-4002	2,4-DNT
6	USGS-4	2,4-DNT

[a] DNT = dinitrotoluene and TCE = trichloroethylene.

other hand, has one contaminated zone near well MWV-24 and five individual wells. For remediation, the extraction wells are assumed to be located in a line orthogonal to the natural groundwater flow direction downstream of the contaminated zone or hot spot. The lengths of the line of wells, W, were estimated from maps of the WSCP and the WSOW and are consistent with estimated maximum widths for the contaminated zones identified.

The minimum number of wells required to contain and clean up a contaminated zone is a function of five parameters: K, B, ∇h, W, and Q. To produce a best-estimate calculation, values for the hydraulic conductivity, K, and vertical extent of contamination, B, were statistically derived from data on wells completed in the weathered and weathered/unweathered zone that are most closely associated with any contaminated zones. That is, K and B were assumed to be equal to the average values for the wells associated with the zone of contamination. Because of the small numbers of wells for each contamination zone, a log normal distribution was not assumed in evaluating the statistical characteristics for the K distribution because of very large standard deviations in the log normal distribution. For individual wells that have contaminant concentrations that exceed their PRG values, K and B were obtained directly from the remedial investigation (DOE and DA 1997) for the given well.

The thickness parameter or vertical extent of contamination, B, was assumed to be equal to the distance between the water table and the depth of an inferred contact between the weathered and unweathered limestone in the Burlington-Keokuk Formation (DOE and DA 1997). This assumption is somewhat more conservative than that used in Section C.3.2.1, in which the thickness of the contaminated zone was assumed to be equal to the difference between the water table and the depth of the screened interval showing contamination. The approach used here was selected to allow contamination to extend beyond the bottom of the screened interval but not beyond the top of the unweathered zone.

Values for the other parameters were obtained as follows. Hydraulic gradient was obtained from a potentiometric surface of the shallow groundwater system (0.01 ft/ft). The width of the contaminated zone was estimated from the locations of the wells showing contamination and an inferred interpretation of the groundwater flow direction obtained from the potentiometric surface for the shallow groundwater aquifer (a value of 1,000 ft was used for all single wells). The maximum, sustainable pumping rate was estimated by using engineering judgment. Generally, a maximum pumping rate of 0.3 gpm was assumed for wells in the WSCP, and a rate of 0.03 gpm was used for wells in the WSOW.

In addition to a more detailed calculation for the contaminated zones and individual wells, uncertainty calculations for the number of wells required for each single well or zone were also performed. The transmitted uncertainty (square root of variance) of a dependent variable, n, that is a nonlinear function of j independent variables, ζ, that have a zero covariance can be expressed by the following relationship (Box et al. 1978):

$$\Delta n = \sqrt{\sum_{i=1}^{j} \left(\frac{\partial n}{\partial \zeta_i}\right)^2 (\Delta \zeta_i)^2} \quad , \qquad \text{(C.7)}$$

where $\Delta\zeta_i$ is the uncertainty in parameter ζ_i, and the summation is carried out over all independent variables. Performing the indicated differentiation on Equation C.7 produces the result

$$\Delta n = \sqrt{T1 + T2 + T3 + T4 + T5} \quad , \qquad \text{(C.8)}$$

where

$$T1 = \left(\frac{2\nabla hKW}{Q}\right)^2 (\Delta B)^2 ,$$

$$T2 = \left(\frac{2BKW}{Q}\right)^2 (\Delta \nabla h)^2 ,$$

$$T3 = \left(\frac{2B\nabla hK}{Q}\right)^2 (\Delta W)^2 ,$$

$$T4 = \left(\frac{2B\nabla hW}{Q}\right)^2 (\Delta K)^2 , \text{ and}$$

$$T5 = \left(\frac{2B\nabla hKW}{Q^2}\right)^2 (\Delta Q)^2 .$$

In carrying out the differentiation, the maximum sustainable pumping rate, Q, was assumed to be independent of the hydraulic conductivity of the formation. In actual practice, there is a relationship between Q and K, but this relationship is further complicated by factors such as well completion and skin effects within the well bore. Because these other processes can significantly affect the relationship between K and Q and because they are, in general, very well-specific, Q was simplistically assumed to be independent of K. Before implementing a pump-and-treat design, additional field work should be done to determine field values for maximum sustainable pumping rates at both the WSCP and the WSOW.

Uncertainties for the hydraulic conductivity and thickness were assumed to be equal to the standard deviation of the values of the wells associated with the zone of contamination (Tables C.2 and C.3). For this statistical method, all wells in the immediate vicinity of a contaminated zone were included in the analysis in order to incorporate as much site-specific data as possible, even though not all wells had concentrations that exceeded their PRGs. For a single well in which the contaminant concentration exceeds its PRG, the uncertainty in the hydraulic conductivity was assumed to be twice the value of the hydraulic conductivity of the associated well. The uncertainty in the vertical extent of contamination, B, was assumed to be 50% of the well value. In some cases, the vertical extent of contamination was estimated from nearby wells because information on the

depth to the contact between the weathered and unweathered zones was not known. The uncertainty in the hydraulic gradient (0.001ft/ft) was assumed to be 10% of the base-case value, 0.001. The uncertainty in the width of the capture line was 100 ft for single wells, and somewhat larger for zones of contamination (Table C.4). The uncertainty in the maximum volumetric rate of pumping was assumed to be equal to 50% of the nominal value. Table C.4 summarizes the relevant parameters and uncertainties for the WSCP and the WSOW.

The number of extraction wells required for each contaminated area and their associated uncertainties are shown in Table C.5. As indicated in this table, a large number of wells would be required to remediate the trichloroethylene (TCE) area at the WSCP. The number of wells required for this contaminated area is also very uncertain, and this uncertainty is primarily the result of the

TABLE C.4 Summary of Parameters and Their Uncertainties Used to Calculate the Number of Extraction Wells under Local Conditions

Contaminated Area[a]	Average K (cm/s)[b]	ΔK (cm/s)	Average B (ft)[b]	ΔB (ft)	Width of Zone (ft)[c]	ΔW (ft)	Maximum Pump Rate (gpm)[d]	ΔQ (gpm)
WSCP								
1	3.3×10^{-3}	7.4×10^{-3}	33.1	3.1	1,800	100	0.30	0.15
2	4.8×10^{-4}	6.0×10^{-4}	20.6	5.9	1,000	100	0.30	0.15
3	3.5×10^{-5}	2.3×10^{-5}	28.4	7.0	1,700	100	0.30	0.15
4	1.3×10^{-3}	1.9×10^{-3}	18.6	7.3	1,200	100	0.30	0.15
5	5.7×10^{-5}	1.1×10^{-4}	5.5	2.8	1,000	100	0.30	0.15
6	4.0×10^{-2}	8.0×10^{-2}	10.3	5.2	1,000	100	3.0	1.5
7	2.9×10^{-5}	5.8×10^{-5}	20.5	10.3	1,000	100	0.30	0.15
8	1.0×10^{-3}	2.0×10^{-3}	15.6	7.8	1,000	100	0.30	0.15
WSOW								
1	1.4×10^{-6}	2.8×10^{-6}	30.7	15.4	1,000	100	0.03	0.015
2	1.5×10^{-7}	3.0×10^{-7}	16.1	8.1	1,000	100	0.03	0.015
3	3.6×10^{-6}	7.2×10^{-6}	23.1	11.5	1,000	100	0.03	0.015
4	1.3×10^{-5}	2.6×10^{-5}	33.4	16.7	1,000	100	0.03	0.015
5	1.0×10^{-3}	2.0×10^{-3}	6.6	3.3	1,000	100	0.30	0.15
6	2.2×10^{-7}	4.4×10^{-7}	55.2	27.6	1,000	100	0.03	0.015

[a] Contaminated zones are defined in Tables C.2 and C.3.

[b] Derived or obtained directly from data in the remedial investigation (DOE and DA 1997).

[c] Estimated from the potentiometric surface for the shallow groundwater aquifer and location of wells that exceed their respective preliminary remediation goals.

[d] Estimated from pump tests at the WSCP.

TABLE C.5 Number of Extraction Wells Required for Implementing a Pump-and-Treat Design at the WSCP and the WSOW

Contaminated Zone[a]	No. of Extraction Wells Needed[b]	Uncertainty in the Number of Extraction Wells Needed[c]	Cleanup Time Based on Travel Path (yr)[d]	No. of Extraction Wells Needed for Cleanup in 10 Years[e]
WSCP				
1	200	450	16	180
2	10	14	22	120
3	2	2	195	340
4	28	45	28	300
5	1	1	43	20
6	41	86	0.2	10
7	1	2	121	60
8	16	33	5	50
Total	299	633		1,080
WSOW				
1	1	1	16,100	1,650
2	1	1	10,500	900
3[f]	1	2	575	340
4	4	8	2,600	920
5	20	42	15	20
6	1	1	9,500	1,550
Total	28	55		5,380

[a] Contaminated zones are defined in Tables C.2 and C.3

[b] Calculated in Equation C.5.

[c] Calculated in Equation C.8.

[d] Calculated in Equation C.12.

[e] Calculated in Equation C.14.

[f] Also included in WSCP contaminated zone 1.

uncertainty in the hydraulic conductivity (i.e., more than 90% of this uncertainty comes from uncertainty in hydraulic conductivity).

At the WSOW, many fewer extraction wells would be required (Table C.5). However, because of the low hydraulic conductivity values, the time required to establish a capture zone and remove the contaminants would be very long.

If the velocity of a contaminant moving toward an extraction well is given by the expression

$$V_r = \frac{Q}{2\pi Br\phi} + V_0 , \qquad \text{(C.9)}$$

where Q is the volumetric extraction rate, ϕ is the effective porosity of the porous medium, and V_0 is the average linear velocity produced by the natural gradient (Freeze and Cherry 1979)

$$V_0 = -\frac{K\nabla h}{\phi} , \qquad \text{(C.10)}$$

then an ordinary, first-order, nonhomogeneous differential can be set up and solved to find the time needed for water to travel from the edge of the contaminated zone to the extraction well. That is,

$$\frac{dr}{dt} - \frac{Q}{2\pi B\phi r} = V_0 . \qquad \text{(C.11)}$$

Equation C.11 can be solved to yield the result

$$L = V_0 t + \sqrt{\frac{Qt}{\pi B\phi}} , \qquad \text{(C.12)}$$

where L is the distance from the edge of the contaminated zone to the extraction well. This equation was then solved iteratively to find the travel time for water.

Although Equation C.12 can be used to estimate the travel time for water, sorption will retard the COCs and increase the travel time. Multiplying the travel time derived from Equation C.12 by the contaminant's retardation factor, R,

$$R = 1 + \frac{\rho K_d}{\phi} , \qquad \text{(C.13)}$$

where K_d is the contaminant's distribution coefficient and ρ is the bulk density of the porous medium, provides an estimate of the contaminant's travel time and an approximate cleanup time for the contaminant.

Equation C.12 was solved for the contaminated areas associated with COCs by using a bulk density of 1.7 g/cm^3 and distribution coefficients of 0.3, 0.5, 0.63, and 1.29 mL/g for TCE, nitrate, 2,4-dinitrotoluene (2,4-DNT), and 2,6-DNT, respectively (DOE 1992; DOE and DA 1997). For contaminated areas that have multiple COCs, the one with the largest K_d was used to bound the calculation. The results of these calculations are given in Table C.5. As expected, the cleanup times for WSOW areas of contamination are exceedingly long because of the low hydraulic conductivity and the small maximum sustainable pumping rates assumed. (Because of very low conductivities, the assumed value of 0.03 gpm may still cause dewatering of the formation, and additional field work will be required before design implementation).

Because of the very long cleanup times estimated for the WSOW, an additional method was used to estimate the number of extraction wells required for a predefined cleanup time of 100 years. In this method, the number of wells was estimated from the volume of water in one pore volume for the contaminated area and the number of pore volumes that must be removed to accomplish cleanup; that is,

$$n = \frac{WLB\phi N}{Q\Delta t} \quad , \qquad \text{(C.14)}$$

where N is the number of pore volumes that must to removed to attain cleanup goals and Δt is the predefined pumping time.

In the absence of dispersion, the number of pore volumes is approximately equal to the retardation coefficient for the COC (Cohen et al. 1997). If dispersion is included in the analyses, the following equation from Cohen et al. (1997) can be used:

$$N = -R \ln\left(\frac{C_w}{C_0}\right) \quad , \qquad \text{(C.15)}$$

where C_0 is the initial concentration of the contaminant and C_w is the cleanup goal. Equation C.15 was not used for this analysis because of the large uncertainty introduced by estimating the value for C_0 for the contaminated areas.

Table C.5 summarizes the number of wells needed in 100 years to clean up the various contaminated areas identified at the WSCP and the WSOW. Many more wells would be required at the WSOW because of its lower hydraulic conductivity and lower assumed maximum sustainable pumping rates.

C.3 PRACTICALITY

As discussed above, at both the WSCP and the WSOW, a large number of extraction wells would be needed to capture and clean up contaminated areas. At the WSCP, a large number of wells would be needed to remediate the TCE-contaminated area. Because of uncertainties in hydraulic conductivities and extraction rates, the uncertainty in the number of wells would also be large. In addition, the presence of potential high-permeability preferred paths could limit the success of a pump-and-treat technology.

In the WSOW, fewer wells would be needed than in the WSCP, but cleanup times would be exceedingly long if the aquifer was not dewatered by the assumed pumping. More efficient cleanup strategies could be developed that incorporate additional wells placed upstream of the capture line.

The design of a practical pump-and-treat system for either the WSCP or the WSOW should proceed in stages. First, a small number of wells should be installed and tested to determine more accurate values for the hydraulic conductivity and maximum sustainable pumping rates in the areas of contamination. Next, a combination of analytical and numerical modeling could be used to determine the locations for additional wells. As more information on the actual groundwater system is obtained from the field, the system design could be modified to produce optimal results.

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APPENDIX D:

DETERMINATION OF CONSTRUCTED WETLAND DESIGN FOR ALTERNATIVE 6: GROUNDWATER REMOVAL, ON-SITE TREATMENT USING PHYTOREMEDIATION

APPENDIX D:

DETERMINATION OF CONSTRUCTED WETLAND DESIGN FOR ALTERNATIVE 6: GROUNDWATER REMOVAL, ON-SITE TREATMENT USING PHYTOREMEDIATION

The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation of potential alternatives for addressing groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively, in St. Charles County, Missouri. This appendix discusses the methodology used to determine the constructed wetland design for Alternative 6, one of eight alternatives analyzed in detail. The methodology applied in this appendix follows that given in Medina and McCutcheon (1996) for the design of a constructed wetland to remediate groundwater contaminated with 2,4,6-trinitro-toluene (2,4,6-TNT) and its breakdown products. The methodology was, however, extended to include consideration of dinitrotoluene (DNT) as well as TNT.

The following assumptions were made for this analysis:

- Reduction of the groundwater contaminants would follow first-order kinetics with regard to contaminant concentrations;
- Transport of groundwater from the constructed wetland would follow plug-flow conditions;
- Plant density would be 15 g/L;
- The depth of the constructed wetland would be limited to 1 m (3 ft) because of the need for light penetration (to allow photolysis of the contaminants);
- The effect of seasonal variation in temperature on the reaction rate was not included (basically due to lack of reaction rate data as a function of temperature);
- A square configuration was applied for the size of the wetland to provide plug-flow conditions.
- Effluent concentrations of the contaminants must satisfy drinking water standards (i.e.. maximum contaminant levels [MCLs]);

- The MCL for 2,4-DNT was applied for 2,6-DNT; and
- The size of the constructed wetland would be primarily impacted by the degradation of the residues of explosives (TNT, DNT). (When trichloroethylene [TCE] was released to water, the primary removal process would be evaporation with a half-life of minutes to hours, depending upon turbulence; the remedial investigation for the groundwater operable unit [DOE and DA 1997] provides a half-life of 3.5 hours for TCE in surface waters.)

The reduction in concentration of contaminant *i* with time follows first-order kinetics of the form:

$$C_i = C_{i,o} \exp(-K_i t) , \qquad \text{(D.1)}$$

where

C_i = effluent concentration of contaminant *i* from constructed wetlands;

$C_{i,o}$ = influent concentration of contaminant *i* into constructed wetland (assumed to be equal to the concentration in the groundwater);

K_i = first-order rate constant for degradation of contaminant *i*; and

t = time.

The first-order constants applied in this analysis are shown in Table D.1.

TABLE D.1 First-Order Rate Constants Applied in Analysis

Contaminant	First-Order Rate Constant (1/d)[a]	Reference
TNT	0.2[b]	Medina and McCutcheon (1996)
DNT (total)[c]	0.043	Todd and Lange (1996)

[a] Based on phytoremediation using the parrot feather (*Myriophyllum brusiliense*) plant.

[b] Includes contributions of breakdown products aminodinitrotoluene, diaminonitrotoluene, and triaminotoluene.

[c] Includes both 2,4-DNT and 2,6-DNT.

Equation D.1 can be rearranged to determine the detention time $t_{D,i}$ (which is the time necessary for a reactor to hold one unit of water to achieve the desired treatment goal) for contaminant i in the constructed wetland:

$$t_{D,i} = -\left\{\ln\left(MCL_i/C_{i,o}\right)\right\} / K_i \ , \qquad \text{(D.2)}$$

where MCL_i = maximum contaminant level of species i (i.e., 2 µg/L for TNT and 0.11 µg/L for DNT).

The total detention time is simply the sum of the individual detention times:

$$t_D = \sum_i t_{D,i} \ . \qquad \text{(D.3)}$$

The empty bed reactor volume, V_e, is calculated on the basis of the total groundwater extraction rate, Q, and the detention time t_D:

$$V_e = Q\, t_D . \qquad \text{(D.4)}$$

The design volume of the constructed wetland, V_{act}, includes also the volume of the plants and a 25% safety factor:

$$V_{act} = V_e \left(1 + \frac{P}{1{,}000}\right) \times 1.25 \ , \qquad \text{(D.5)}$$

where P = plant density (g/L).

The area of land, A, needed for the constructed wetland was calculated for a wetland depth of 1 m (3 ft):

$$A = V_{act}/3 \text{ ft} \ , \qquad \text{(D.6)}$$

The length, L, of the constructed wetland was calculated for a square configuration:

$$L = \sqrt{A} \ . \qquad \text{(D.7)}$$

These equations, together with contaminant concentrations given in the remedial investigation report (DOE and DA 1997), were used to determine the characteristics of a constructed wetland for both the WSCP and WSOW areas.

The results of the analysis indicated that the degradation of DNT would be the rate-limiting step in the constructed wetland design. The kinetics of the reaction of DNT to form degradation

products is based upon laboratory studies that may not reflect degradation rates under actual conditions. Thus, the design discussed here would be modified by using specific rate data for the WSCP and WSOW when available.

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APPENDIX E:

MODELING OF TRICHLOROETHENE CONTAMINANT TRANSPORT AND DEGRADATION USING THE TRANSPORT CODE "BIOSCREEN"

APPENDIX D:

MODELING OF TRICHLOROETHENE CONTAMINANT TRANSPORT AND DEGRADATION USING THE TRANSPORT CODE "BIOSCREEN"

The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation of potential alternatives for addressing groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively, in St. Charles County, Missouri. This appendix presents the transport modeling performed to determine the potential future migration of trichloroethene (TCE) in order to evaluate whether Alternative 2 (Monitoring with No Active Remediation) would be a viable option for groundwater cleanup at the WSCP.

E.1 DESCRIPTION OF *BIOSCREEN* MODEL

A protocol has been developed for determining the feasibility and effectiveness of natural attenuation in remediating groundwater contaminated with chlorinated aliphatic hydrocarbons (such as TCE) for use at DA and DOE sites; this protocol is summarized in Wiedemeier et al. (1996). Consideration of natural attenuation as a potential option requires modeling and evaluation of contaminant degradation rates and pathways. The primary objective of site modeling is to demonstrate that natural processes of contaminant degradation would reduce contaminant concentrations below regulatory standards before potential exposure pathways would be encountered.

Several analytical solute transport models are available to compare the rates of contaminant transport and natural attenuation of chlorinated aliphatic hydrocarbons in groundwater (Goffredi 1997). One such nonproprietary model, the BIOSCREEN model of the U.S. Environmental Protection Agency (EPA 1996), is available from the Robert S. Kerr Laboratory via the Internet at http://www.epa.gov/ada/bioscreen.html.

The BIOSCREEN model is an easy-to-use screening tool that has been programmed into a Microsoft^{R} Excel spreadsheet. It is based on the Domenico analytical solute transport model (Domenico 1987) and is designed to estimate three-dimensional contaminant transport for dissolved phase hydrocarbons in the saturated zone under the influences of oxygen, nitrate, iron, sulfate, and

methane-limited biodegradation. The processes considered by the model include advection, dispersion, adsorption, first-order decay, and instantaneous reactions under aerobic and anaerobic conditions. The model has been designed to simulate remediation through natural attenuation of dissolved hydrocarbons and contains two options for simulating in-situ biodegradation: first-order decay and instantaneous reaction.

The BIOSCREEN model was used in this analysis to predict the maximum extent of contaminant migration, which was then compared with the distance to potential points of exposure. Analytical groundwater transport models such as BIOSCREEN have recently been widely applied for this purpose (e.g., American Society for Testing and Materials 1995).

E.2 BIODEGRADATION RATE CONSTANT

Because biodegradation has been assumed to be the most important degradation process for natural attenuation of potential TCE contaminant migration, the biodegradation rate is very important in determining whether Alternative 2 (Monitoring with No Active Remediation) would be feasible for groundwater cleanup at the WSCP.

The kinetics of biodegradation of TCE, a chlorinated aliphatic hydrocarbon, is generally represented as a first-order rate constant normalized for the effects of any dilution and volatilization. The degradation of TCE by various microbe populations has been extensively studied (Hopkins et al. 1993; Krumme et al. 1993; Enzien et al. 1994; Lu et al. 1995; Leahy et al. 1996). TCE is clearly degraded by these microbe populations, but many factors appear to be important in determining the rate of degradation (e.g., the addition of a carbon substrate such as toluene, benzene, or phenol supplies energy to the microbes, which greatly enhances the degradation of TCE; and long-term degradation rates of TCE [greater than three months] appear to be limited by a slow desorbtion rate of TCE from the aquifer solids into the aqueous phase). A literature review (Smith and Dragun 1984; Montgomery 1996; Wilson et al. 1996) indicated that a potentially wide range in first-order rate constants exists, apparently because of the factors influencing the rate of degradation. Thus, a site-specific biodegradation rate based upon available data from the actual conditions at the WSCP would be the most accurate approach for determining the potential attenuation of any future migration of TCE contamination in the groundwater.

Microbial degradation of TCE through sequential dehalogenation produces 1,2-dichloroethylene (1,2-DCE) and vinyl chloride. Measured concentrations of TCE and 1,2-DCE in groundwater monitoring wells at the WSCP as a function of time (DOE and DA 1997) were used in this analysis to estimate the first-order rate constant for degradation of TCE to form 1,2-DCE. Assuming that the conversion of 1,2-DCE into other degradation products (such as vinyl chloride) is much slower than the conversion of TCE into 1,2-DCE (which agrees with rate data given in Smith and Dragun [1984] and Montgomery [1996]), the equation for formation of 1,2-DCE over time is as follows:

$$[1,2\text{-DCE } (\mu g/L)] = [\text{TCE } (\mu g/L)]_0 \times [1 - \exp(-k \times time)] , \qquad (E.1)$$

where $[\text{TCE } (\mu g/L)]_0$ is the initial concentration of TCE in the groundwater at time "0" (i.e., source term) and k is the first-order rate constant. The initial TCE concentration, which is unknown, can be determined using the following equation for the reduction of TCE concentration over time:

$$[\text{TCE } (\mu g/L)] = [\text{TCE } (\mu g/L)]_0 \times \exp(- k \times time) . \qquad (E.2)$$

Inserting this equation into the equation for formation of 1,2-DCE gives:

$$[1,2\text{-DCE } (\mu g/L)] = [\text{TCE } (\mu g/L)] \times [\exp(- k \times time) - 1] , \qquad (E.3)$$

which can be rearranged to determine the first-order rate constant k, as follows:

$$k = \text{LN}\{1 + [1,2\text{-DCE } (\mu g/L)] / [\text{TCE } (\mu g/L)]\} / time . \qquad (E.4)$$

The results of determining the rate constant k using Equation E.4 is provided in Figure E.1. The value of k ranges from 1.2×10^{-5} d^{-1} to 9.6×10^{-5} d^{-1}, on the basis of the data provided in the remedial investigation for the groundwater operable units (GWOU RI) (DOE and DA 1997) and assuming that the initial release occurred on June 1, 1995. (These data can be considered to be conservative because the TCE release might have occurred in the summer and fall of 1995 (DOE and DA 1997); the assumption of a later date would result in a greater rate constant and faster biodegradation of TCE in the shallow aquifer at the WSCP.) This analysis applies the average value of approximately 5×10^{-5} d^{-1} (1.7×10^{-2} yr^{-1}) as the first-order rate constant for TCE degradation in the transport model BIOSCREEN.

Monitoring Well Location	Date Well Sampled	Groundwater Concentration (ug/L)		Assumed Release Date	First-Order Rate Constant (1/d)
		1,2-DCE	TCE		
GW-2037	Sep 96	25	810	Jun-95	6.6E-05
GW-2038	Apr 96	22.7	766	Jun-95	9.6E-05
GW-2038	Jun 96	39	9,000	Jun-95	1.2E-05
GW-2038	Sep 96	14	1,050	Jun-95	2.9E-05
GW-3024	Sep 96	0.97	59.8	Jun-95	3.5E-05
Average (per day)					***4.8E-05***
Average (per year)					***1.7E-02***
Half-Life (years)					***40***

The FIRST-ORDER RATE CONSTANT is determined by the following eqn:

[First-Order Rate Constant] = LN{ 1 + [1,2-DCE Conc.] / [TCE Conc.] } / { [Date Well Sampled] - [Assumed Release Date] }

which is based upon the following assumptions:

- ***Conversion of TCE to 1,2-DCE follows first-order kinetics***
- ***Conversion of 1,2-DCE into other degradation products is essentially a slow process (and can be neglected).***

Source: DOE and DA (1997).

FIGURE E.1 Estimation of the First-Order Rate Constant for Microbial Degradation of TCE at the WSCP

The solute half-life was determined by the following equation:

$$[\textit{Solute Half-Life}\ (\text{yr})] = \text{LN}(2) / k \qquad \text{(E.5)}$$

and has a value of approximately 40 years. The solute half-life of 40 years, which was determined for this analysis by using site-specific concentration data for the WSCP is much greater than the generic value of 0.3 year generally assumed for microbial degradation of TCE (Smith and Dragun 1984).

E.3 MODEL INPUTS

The input parameters necessary for simulation of contaminant transport using the BIOSCREEN model are shown in Figure E.2. The values shown in Figure E.2 for the Instantaneous Reaction Model are designed to be generic in nature and were not applied in this analysis.

The values applied in this study are provided in Table E.1. In general, these values would be expected to result in greater contaminant transport and thereby a greater potential for impacts to any receptors.

E.4 SIMULATION RESULTS AND CONCLUSIONS

Steady-state conditions were approximated by assuming a very long simulation time of 1,000 years. The preliminary results from BIOSCREEN indicate the following:

- Consideration of adsorption as the only means to retard contaminant migration might result in erroneous conclusions concerning the contaminant concentration along the centerline. As shown in Figure E.3, the centerline concentration considering only adsorption (listed as "No Degradation") is much greater than that considering microbial degradation ("1st Order Decay") and remains above the applicable or relevant and appropriate requirement (ARAR) of 5.0 µg/L (0.005 mg/L) for distances greater than 1,000 m (3,000 ft). This indicates that microbial degradation of TCE has a significant impact on its estimated transport and that site-specific biodegradation rates are necessary to accurately predict contaminant transport.
- Applying a half-life of 40 years for microbial degradation of TCE, the maximum extent of TCE contamination above the ARAR of 5.0 µg/L (0.005 mg/L), considering microbial decay (i.e., the 1st Order Decay option), would be limited to a distance of less than 1,000 m (3,000 ft) downstream of its current location (see Figures E.3 and E.4). The distance of 1,000 m (3,000 ft) is shorter than the distance to potential points of exposure (i.e., the groundwater discharge areas at the surface springs).

BIOSCREEN Natural Attenuation Decision Support System

Air Force Center for Environmental Excellence — *Version 1.3*

Weldon Spring TCE at Chem Plant — Run Name

Data Input Instructions:

115 ↑ or 0.02 — 1. Enter value directly....or 2. Calculate by filling in grey cells below. (To restore formulas, hit button below).

Variable* — Data used directly in model.

20 — Value calculated by model. (Don't enter any data).

1. HYDROGEOLOGY

Seepage Velocity*	Vs	14.6	(ft/yr)
or		↑ or	
Hydraulic Conductivity	K	8.8E-05	(cm/s)
Hydraulic Gradient	i	0.04	(ft/ft)
Porosity	n	0.25	(-)

2. DISPERSION

Longitudinal Dispersivity*	alpha x	25.5	(ft)
Transverse Dispersivity*	alpha y	2.5	(ft)
Vertical Dispersivity*	alpha z	0.0	(ft)
or		↑ or	
Estimated Plume Length	Lp	1100	(ft)

3. ADSORPTION

Retardation Factor*	R	1.6	(-)
or		↑ or	
Soil Bulk Density	rho	2.4	(kg/L)
Partition Coefficient	Koc	126	(L/kg)
FractionOrganicCarbon	foc	5.00E-04	(-)

4. BIODEGRADATION

1st Order Decay Coeff*	lambda	1.7E-2	(per yr)
or		↑ or	
Solute Half-Life	t-half	40.00	(year)
or Instantaneous Reaction Model			
Delta Oxygen*	DO	5.78	(mg/L)
Delta Nitrate*	NO3	17	(mg/L)
Observed Ferrous Iron*	Fe2+	11.3	(mg/L)
Delta Sulfate*	SO4	100	(mg/L)
Observed Methane*	CH4	0.414	(mg/L)

5. GENERAL

Modeled Area Length*	3000	(ft)
Modeled Area Width*	330	(ft)
Simulation Time*	1000	(yr)

6. SOURCE DATA

Source Thickness In Sat.Zone* 50 (ft)

Source Zones:

Width* (ft)	Conc. (mg/L)*
50	1.05
25	1.05
100	1.05
25	1.05
50	1.05

Source Decay (see Help):

SourceHalflife*	FALSE	(yr)
Soluble Mass	↑ or	
In NAPL, Soil	1483	(Kg)

Vertical Plane Source: Look at Plume Cross-Section and Input Concentrations & Widths for Zones 1, 2, and 3

View of Plume Looking Down

Observed Centerline Concentrations at Monitoring Wells If No Data Leave Blank or Enter "0"

7. FIELD DATA FOR COMPARISON

Dist. from Source (ft)	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
Concentration (mg/L)											

8. CHOOSE TYPE OF OUTPUT TO SEE:

RUN CENTERLINE — View Output

RUN ARRAY — View Output

Help — Recalculate This Sheet

Paste Example Dataset

Restore Formulas for Vs, Dispersivities, R, lambda, other

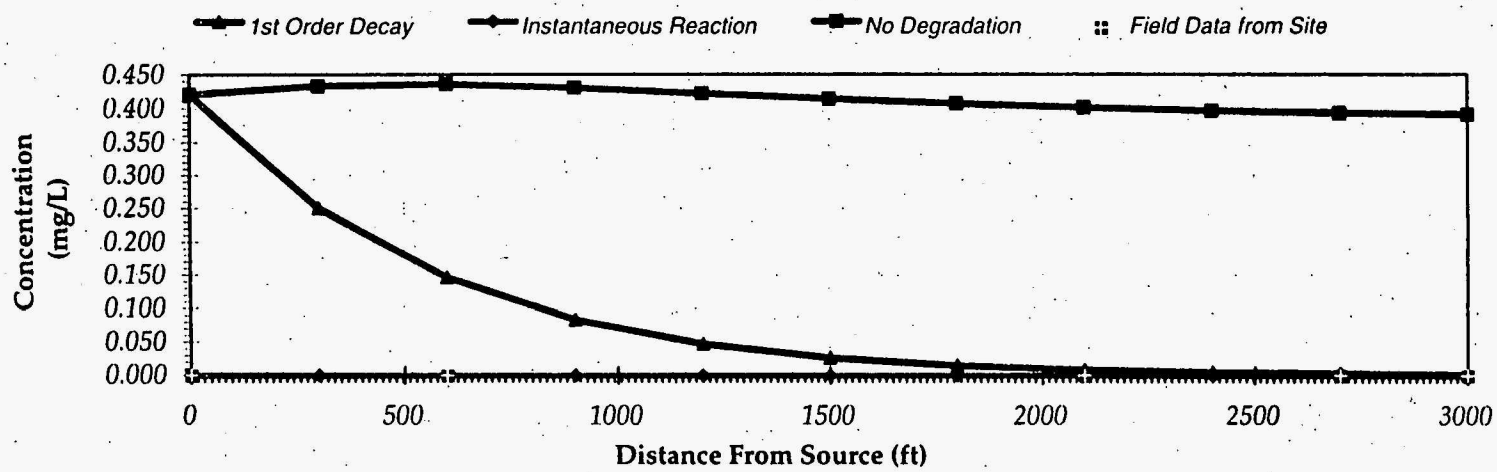
FIGURE E.2 BIOSCREEN Input Screen to Simulate TCE Transport at the WSCP

TABLE E.1 Input Parameters for BIOSCREEN Computer Model

BIOSCREEN Parameter	Value	Units	Explanation/Reference(s)
1. Hydrogeology			
Hydraulic conductivity	8.8E-05	cm/s	Based upon 0.25 ft/d given in GWOU RI (DOE and DA 1997).
Hydraulic gradient	0.04	ft/ft	Upper-range value given in GWOU RI (DOE and DA 1997).
Porosity	0.25	–	Upper-range value based upon Freeze and Cherry (1979).
2. Dispersion			
Estimated plume length	1,100	ft	Based upon distance from monitoring well MW-3024/3025 (northeastern edge of known TCE contamination) to well MWS-21 (southwestern edge of known TCE contamination).
3. Adsorption			
Soil bulk density	2.4	kg/L	Based upon Freeze and Cherry (1979).
Partition coefficient	126	L/kg	Based upon Montgomery (1996).
Fraction organic carbon	5.0E-04	–	Based upon Schumacher et al. (1992).
4. Biodegradation			
Solute half-life	40	year	Estimated based upon available concentration data for TCE and 1,2-DCE (see text).
5. General			
Modeled area length	3,000	ft	Assumed, varied to accommodate TCE contaminant migration.
Modeled area width	330	ft	Based upon a plume width of 100 m, which was estimated on the basis of the upper-range lateral distance between the monitoring wells where TCE contamination has been measured.
Simulation time	1,000	year	Assumed, to achieve steady-state conditions.
6. Source Data			
Source thickness	50	ft	Upper range value given in GWOU RI (DOE and DA 1997) for the weathered bedrock aquifer.
Source zone concentration	1.05	mg/L	Based upon the highest level of TCE contamination in groundwater samples taken during September/October 1996. Constant value assumed for conservatism.
Soluble mass in NAPL, soil	1,480	kg	Based upon the highest level of TCE (4,800 µg/kg) measured in soil samples and assumed dimensions of TCE-contaminated aquifer: (330 ft × 1,100 ft × 50 ft × 25% <porosity>) × (2.4 g/mL × 62.43 lb/ft^3/ 2.2 lb/kg) × (4,800 µg/kg/1 × 10^9 µg/kg).

DISSOLVED HYDROCARBON CONCENTRATION ALONG PLUME CENTERLINE (mg/L at Z=0)

TYPE OF MODEL	Distance from Source (ft) 0	300	600	900	1200	1500	1800	2100	2400	2700	3000
No Degradation	0.421	0.433	0.436	0.431	0.423	0.415	0.408	0.402	0.397	0.394	0.391
1st Order Decay	0.421	0.251	0.146	0.084	0.048	0.027	0.015	0.009	0.005	0.003	0.002
Inst. Reaction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Field Data from Site											



Calculate Animation

Time: 1,000 Years

Return to Input

Recalculate This Sheet

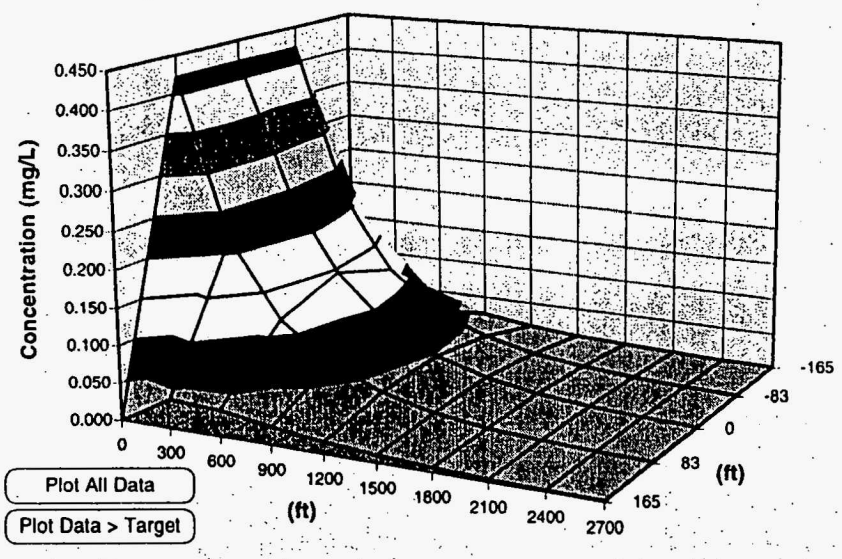
FIGURE E.3 Centerline Output for TCE Contaminant Concentration at the WSCP

DISSOLVED HYDROCARBON CONCENTRATIONS IN PLUME (mg/L at Z=0)

Transverse Distance (ft) ↓ / Distance from Source (ft) →	0	300	600	900	1200	1500	1800	2100	2400	2700	3000
165	0.000	0.038	0.035	0.025	0.016	0.010	0.006	0.004	0.002	0.001	0.001
83	0.421	0.217	0.117	0.066	0.038	0.022	0.013	0.007	0.004	0.002	0.001
0	0.421	0.251	0.146	0.084	0.048	0.027	0.015	0.009	0.005	0.003	0.002
-83	0.421	0.217	0.117	0.066	0.038	0.022	0.013	0.007	0.004	0.002	0.001
-165	0.000	0.038	0.035	0.025	0.016	0.010	0.006	0.004	0.002	0.001	0.001

Model to Display:
- No Degradation Model
- 1st Order Decay Model
- Instantaneous Reaction Model

Time: 1000 Years Target Level: 0.005 mg/L Displayed Model: 1st Order Decay



Plot All Data

Plot Data > Target

Plume and Source Masses (Order-of-Magnitude Accuracy)

Plume Mass if No Biodegradation	Can't Calc.	(Kg)
- Actual Plume Mass	Can't Calc.	(Kg)
= Plume Mass Removed by Biodeg	-	(Kg)

Change in Electron Acceptor/Byproduct Masses:

Oxygen	Nitrate	Iron II	Sulfate	Methane	
na	na	na	na	na	(Kg)

Original Mass in Source (Time = 0 Years)	1483.3	(Kg)
Mass in Source Now (Time = 1000Years)	594.7	(Kg)
Current Volume of Groundwater in Plume	Can't Calc.	(ac-ft)
Flowrate of Water Through Source Zone	Can't Calc.	(ac-ft/yr)

Mass HELP Recalculate

FIGURE E.4 Concentration Contours for TCE Contamination at the WSCP

Application of the lowest estimated value for the first-order degradation rate constant (i.e., 1.2×10^{-5} d^{-1}, as shown in Figure E.1) results in the calculated distance to the ARAR of 5 µg/L increasing to approximately 1,400 m (4,500 ft), with the TCE contamination still being confined within the boundaries of the WSCP.

The transport modeling results using BIOSCREEN and applying the recommended first-order biodegradation rate option indicate that natural processes would likely maintain TCE concentrations below remediation goals before potential receptors were reached, primarily due to dilution and biodegradation. However, additional site characterization might be necessary to more fully establish the potential contribution of natural processes to attenuation of the contaminant concentrations at the WSCP.

Although the BIOSCREEN model incorporates a number of simplifying assumptions that could potentially contribute to uncertainty in the modeling results, these results suggest that active remediation might not be necessary and that Alternative 2 (Monitoring with No Active Remediation) considered in the GWOU feasibility study might be an appropriate approach for managing the TCE contamination at the WSCP.

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APPENDIX F:

METHODOLOGY AND ASSUMPTIONS USED TO DETERMINE THE COSTS OF THE VARIOUS ALTERNATIVES IN THIS FEASIBILITY STUDY

APPENDIX F:

METHODOLOGY AND ASSUMPTIONS USED TO DETERMINE THE COSTS OF THE VARIOUS ALTERNATIVES IN THIS FEASIBILITY STUDY

The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation of potential alternatives for addressing groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively, in St. Charles County, Missouri. This appendix discusses the methodology and assumptions used to determine the costs of the various alternatives considered in this feasibility study (FS). Unless noted otherwise, the direct costs for both construction and operational phases were developed using Version 3.20 of the Remedial Action Cost Estimating and Requirements System (RACER) computer model (Delta Research Corporation 1995).

F.1 REMEDIAL ACTION COST ESTIMATING AND REQUIREMENTS SYSTEM (RACER) SYSTEM

The RACER system was developed by the U.S. Air Force to estimate the total cost (both direct and indirect) of remedial actions. RACER is a PC-based environmental cost-estimating system that can be used to provide programming, budgeting, and cost engineering support during various phases of remediation: Studies (PA/SI, Petroleum Underground Storage Tank [UST] Site Assessment, Remedial Investigation [RI]/FS, and RFI/CMS), Remedial Design, Remedial Action (including Operations and Maintenance [O&M]), and Site Work and Utilities.

The RACER estimating process involves a series of basic steps, including calculation of site (direct) costs and project costs. A project may consist of a single site or it may contain several sites. For each site included in the project, the user can select and run the technologies and/or processes (cost models) that will be used to remediate the site. The costs calculated for these models are direct costs only (i.e., the cost does not include contractor overhead and profit, cost for contingencies, project management, or escalation). Once direct costs have been calculated for all cost models included in each site of the project, the user completes the estimate by calculating the project costs. Project costs include costs for contractor overhead and profit, contingencies, project management, and escalation. RACER was used in this analysis to determine only the direct costs (costs that can be directly attributed to a particular item of work or activity). Specific indirect cost

relationships for the WSCP and WSOW were applied in this analysis rather than the generic indirect cost relationships provided by the RACER model.

RACER uses a parametric modeling technique similar to the U.S. Air Force's Construction Cost Management Analysis System (CCMAS). The basic concept of RACER is that predefined engineering relationships link primary parameters to detailed quantities. These quantities are then priced using established cost databases. The RACER cost models are based on generic engineering solutions for environmental projects, technologies, and processes. The engineering solutions were derived from research, government laboratories, construction management agencies, vendors, contractors, engineering analyses, and historic project information. Design parameters within the cost models were tailored by the cost estimator to reflect specific project conditions and requirements. The design was then tailored by RACER into specific quantities of work, which were priced using current price data. The assembly cost database within RACER was developed from the *Unit Price Book* of the U.S. Army Corps of Engineers (1989) and supplemented by vendor and contractor quotes. A cost differential was included in this analysis to account for the differences in material and labor costs in the Weldon Spring area compared with the generic *Unit Price Book* costs.

Professional labor includes activities that provide interpretation of the performance of the remedial action during both the construction/startup and O&M phases of the environmental restoration process. Typical professional labor activities associated with remedial action construction include oversight of construction activities, permit acquisition, and "as built" drawings. Professional labor activities associated with O&M include evaluation of sampling and analysis data, comparison of results with project goals, coordination of field activities, and documentation and reporting of all efforts. Estimates of professional labor were derived by RACER using a parametric approach based on similar levels of activities for related projects.

F.2 ESTIMATION OF INDIRECT COSTS

Indirect costs are defined as those costs that cannot be identified specifically with a particular activity, cannot be charged to a specific element of work, or do not become a permanent part of any facility constructed. Indirect costs — small tools and supplies, fringes, insurance, and contingency — were estimated on the basis of various percentages of other costs specific to the WSCP (Hood 1997) and the WSOW (Patton et al. 1996). The various indirect cost relationships

applied in this analysis are provided in Tables F.1 and F.2 and were implemented using a Microsoft Excel™ spreadsheet for each alternative.

Contingency costs are added to a project to cover costs that may result from incomplete design, unforeseen and unpredictable conditions, or uncertainties within the defined scope. In general, the contingency cost is derived from the difference between the 5% and 50% chance of overrun of the base estimate. A contingency percentage of 25% was applied for the WSCP in this analysis, based upon Hood (1997), which is within the range recommended by the DOE Office of Environmental Management for projects in the preliminary stage of the remediation process (DOE 1990).

F.3 PRESENT-WORTH ANALYSIS

Present worth is defined as the investment-evaluation procedure that involves discounting the sums of capital investment, O&M, and repairs at a specified interest rate (representing cost of capital or minimum acceptable rate of return). The following analysis complies with the requirements described by the Office of Management and Budget (OBM) Circular No. A-94, the National Bureau of Standards Handbook 135 prepared for DOE, and the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) Directive 9355.3-01 (EPA 1988) for adjusting for converting cash flows at different times to correspond at a common time during preparation of a cost estimate.

The costs calculated in this analysis are given in 1995 constant dollars. The constant dollar cash flows occurring at different times were converted by the present-worth analysis into a time-equivalent lump sum amount evaluated at the beginning of the base year. This conversion was performed by using an interest rate or "real discount rate" that reflects the opportunity cost apart from any change in the purchasing power of the dollar. A Uniform Series Present Worth Factor (P/A) was calculated by using the real discount rate i:

$$[P/A] = [\ (1+i)^n - 1\ ] / i / (1+i)^n ,$$

where n is the project duration.

TABLE F.1 WSCP-Specific Indirect Cost Relationships Applied in This FS

Indirect Cost Component	Relationship	Applied Under
Small tools and supplies	5% of total direct labor cost	Cost of supplies
Level D personnel protection	0.179 × direct workforce	Cost of supplies
State sales and use tax	7.23% of cost of permanent materials and supplies	Cost of permanent materials and supplies
Indirect labor	25% of total direct labor cost	Cost of OH/Fee/Con[a]
Plant operations	8.8% of total direct labor cost	Cost of OH/Fee/Con
Fringes	29% of indirect labor	Cost of OH/Fee/Con
Margin	10% of sum of direct cost and all preceding indirect cost components	Cost of OH/Fee/Con
Bond	2% of sum of direct cost and all preceding indirect cost components	Cost of OH/Fee/Con
Insurance	10% of sum of direct cost and all preceding indirect cost components	Cost of OH/Fee/Con
Contingency	25% of sum of direct cost and all preceding indirect cost components	Cost of OH/Fee/Con

[a] OH/Fee/Con = overhead/performance fee/contingency.

Source: Data from Hood (1997).

A discount rate of 7% (before taxes and after inflation) was applied in this analysis (EPA 1993). Although remedial activities would continue for a reasonable amount of time (i.e., greater than 10 years) or until remedial objectives were met, long-term operation costs were based on a 30-year period, per instructions in EPA (1988), and include annual sampling and analysis costs.

F.4 SAMPLE CONSTRUCTION COST CALCULATION FOR ALTERNATIVE 2

The construction of approximately 10% of the number of existing wells (i.e., 15 additional wells) was conservatively assumed in Alternative 2 (Monitoring with No Active Remediation) to

TABLE F.2 WSOW-Specific Indirect Cost Relationships Applied in This FS

Indirect Cost Component	Relationship	Applied Under
Contractor overhead	5% of total direct labor cost	Cost of OH/Fee/Con[a]
Contractor profit	8% of sum of direct cost and all preceding indirect cost components	Cost of OH/Fee/Con
Contingency	10% of sum of direct cost and all preceding indirect cost components	Cost of OH/Fee/Con
Project management	8% of sum of direct cost and all preceding indirect cost components, excluding contingency	Cost of OH/Fee/Con

[a] OH/Fee/Con = overhead/performance fee/contingency.

Source: Data from Patton et al. (1996).

evaluate the protectiveness of this alternative. The following assumptions were made during development of the construction costs for Alternative 2:

- Well installation would be in a consolidated formation;
- Safety Level D conditions would be maintained during construction (Level D provides minimal protection against respiratory hazards. Coveralls, hard hat, leather or chemical-resistant boots/shoes, and safety glasses or chemical splash goggles are required. Personal dosimeters are included for Level D radioactive sites.);
- Construction materials would be stainless steel (for long-term effectiveness);
- Fifteen wells would be developed with the following characteristics:
  - Well diameter, 5 cm (2 in.);
  - Depth to top of screen, 20 m (65 ft);
  - Screen length, 3 m (10 ft); and
- Dedicated pumps would be provided for each well for purge and sampling purposes.

This information was used with the RACER model to determine the direct construction costs. The indirect cost relationships provided in Tables F.1 and F.2 were then applied to determine the total construction cost (direct and indirect). Estimates of the direct costs are given in Table F.3.

F.5 EXAMPLE OF A PRESENT-WORTH COST CALCULATION FOR ALTERNATIVE 2

Costs for Alternative 2 would be associated with continuing the existing environmental monitoring program, constructing and operating the proposed additional monitoring wells, and conducting a performance review every five years. The methodology outlined in Section F.3 was implemented within a Microsoft Excel™ spreadsheet, as shown in Table F.4. The spreadsheet methodology was developed to allow a variable discount rate and operations duration, to allow for consideration of different "what-if" scenarios.

TABLE F.3 Estimated Direct Costs for Alternative 2 (Monitoring with No Active Remediation)[a]

Description (WBS Element)	Quantity	Unit	Work Force (person-hours)	Cost ($) Labor	Equipment	Permanent Materials	Supplies	Subcontracts	OH/Fee/Con	Total
15 Groundwater Monitoring Wells in Burlington/Keokuk Limestone (33.02.04.01)										
55-gal drums for drilling cuttings and developing water	32	Each	0	0	0	1,357	0	0	0	1,357
Well development equipment rental	2	Week	6	77	1	754	0	0	0	832
Split-spoon sample, 2 in. × 24 in., during drilling	228	Each	0	0	0	5,643	0	0	0	5,643
Organic vapor analyzer, rental, per day	0	Day	0	0	0	0	0	0	0	0
Mud drilling, 6-in.-diameter borehole	1,140	LNFT	749	10,342	13,276	0	0	0	0	23,618
Surface pad, concrete, 2 in. × 2 in. × 4 in.	15	Each	2	15	1	40	0	0	0	55
5-ft guard posts, cast iron, concrete fill	60	Each	123	1,700	22	1,461	0	0	0	3,184
H stem, 8 in. outside diameter borehole for 2-in. well	0	LNFT	0	0	0	0	0	0	0	0
2-in. well, bentonite seal	15	Each	7	94	120	215	0	0	0	429
2-in. well, portland cement grout	915	LNFT	0	0	0	815	0	0	0	815
2-in. screen, filter pack	195	LNFT	23	306	393	1,132	0	0	0	1,831
2-in. stainless steel, well casing	1,013	LNFT	160	2,209	2,834	15,723	0	0	0	20,766
2-in. stainless steel, well screen	150	LNFT	21	277	356	6,027	0	0	0	6,660
2-in. stainless steel, well plug	15	Each	7	83	107	377	0	0	0	567
Groundwater pump, 3/4 HP, controls	15	Each	251	3,465	38	66,023	0	0	0	69,526
Mobilization/demobilization drilling rig and crew	1	LS	41	554	711	0	0	0	0	1,266
Moving rig/equipment around site	14	Each	18	243	311	0	0	0	0	554
Drilling & Installation (33.23.11.01)										
Monitoring well slug testing equipment rental	15	Week	0	0	0	10,692	0	0	0	10,692

TABLE F.3 (Cont.)

Description (WBS Element)	Quantity	Unit	Work Force (person-hours)	Cost ($) Labor	Equipment	Permanent Materials	Supplies	Subcontracts	OH/Fee/Con	Total
Construction Support (33.80.01.01)										
Project engineer	12	hour	12	410	0	0	0	0	0	411
Staff engineer	120	hour	120	3,124	0	0	0	0	0	3,124
Staff hydrogeologist	0	hour	0	0	0	0	0	0	0	0
Field technician	120	hour	120	1,973	0	0	0	0	0	1,973
Certified industrial hygienist	6	hour	6	206	0	0	0	0	0	206
Junior geologist	60	hour	60	904	0	0	0	0	0	904
Other direct costs	1	LS	0	0	0	95	0	0	0	95
"As Built" Drawings (33.80.01.04)										
Staff engineer	2	hour	2	52	0	0	0	0	0	52
Surveyor	3	hour	3	62	0	0	0	0	0	62
Field technician	4	hour	4	66	0	0	0	0	0	66
Draftsman/CADD operator	12	hour	12	197	0	0	0	0	0	197
Word processing/clerical	4	hour	4	55	0	0	0	0	0	55
Other direct costs	1	LS	0	0	0	6	0	0	0	6
Monitoring Reports (33.80.01.06)										
Project engineer	8	hour	8	274	0	0	0	0	0	274
Staff engineer	12	hour	12	312	0	0	0	0	0	312
Staff hydrogeologist	16	hour	16	416	0	0	0	0	0	416
Field technician	24	hour	24	395	0	0	0	0	0	395
Draftsman/CADD operator	56	hour	56	921	0	0	0	0	0	921
Word processing/clerical	24	hour	24	329	0	0	0	0	0	329
Other direct costs	1	LS	0	0	0	38	0	0	0	38

TABLE F.3 (Cont.)

Description (WBS Element)	Quantity	Unit	Work Force (person-hours)	Cost ($) Labor	Equipment	Permanent Materials	Supplies	Subcontracts	OH/Fee/Con	Total
Sampling and Analysis Plan (33.80.01.24)										
Project engineer	2	hour	2	69	0	0	0	0	0	69
Staff engineer	8	hour	8	208	0	0	0	0	0	208
Word processing/clerical	8	hour	8	110	0	0	0	0	0	110
Certified industrial hygienist	2	hour	2	69	0	0	0	0	0	69
Other direct costs	1	LS	0	0	0	6	0	0	0	6
Health and Safety Plan (33.80.01.32)										
Project engineer	6	hour	6	206	0	0	0	0	0	206
Certified industrial hygienist	60	hour	60	2,055	0	0	0	0	0	2,055
Other direct costs	1	LS	0	0	0	33	0	0	0	33
Work Plan Amendments (33.80.01.46)										
Project engineer	15	hour	15	514	0	0	0	0	0	514
Staff engineer	36	hour	36	937	0	0	0	0	0	937
Word processing/clerical	48	hour	48	658	0	0	0	0	0	658
Certified industrial hygienist	15	hour	15	514	0	0	0	0	0	514
Other direct costs	1	LS	0	0	0	38	0	0	0	38
Total Direct Cost			**2,091**	**34,398**	**18,170**	**110,474**	**0**	**0**	**0**	**163,042**

[a] Abbreviations: CADD = computer-aided design and drafting; LNFT = linear foot; LS = lump sum; OH/Fee/Con = overhead/performance fee/contingency; and WBS = work breakdown structure.

TABLE F.4 Present-Worth Cost Calculation for Alternative 2 (Monitoring with No Active Remediation)

Item Description	Quantity	Unit	Duration (yr)	Unit Cost ($/unit)	Cost (current $)	Present-Worth Cost ($)
Discount rate (%):	7%					
Operations duration (yr):	30					
Capital Costs						
Direct cost, proposed groundwater monitoring wells	15	Wells	–	10,867	163,000	163,000
Indirect cost, proposed groundwater monitoring wells					127,000	127,000
Well restrictions	1	LS	–	20,000	20,000	20,000
Total Capital Costs					**310,000**	**310,000**
Annual Costs						
Groundwater monitoring, sampling labor, DOE	73	Wells	30	3,195	6,998,000	2,895,000
Groundwater monitoring, analytical costs, DOE (based upon 81 samples per round, annual sampling; $210 analysis cost per sample)	73	Wells	30	233	510,000	211,000
Groundwater monitoring, 15 proposed wells	15	Wells	30	3,600	1,620,000	670,000
Groundwater monitoring, WSOW wells (assumed to be sampled annually rather than quarterly, as applied in the FS for the WSOW [DA 1993])	79	Wells	30	457	1,082,000	448,000
Performance review (every 5 years)	1	Per 5 yr	30	100,000	600,000	239,000
Total Postclosure Costs					**10,810,000**	**4,463,000**
Present-Worth Costs						
Capital costs					310,000	310,000
Annual costs					10,810,000	4,463,000
Total Cost					**11,120,000**	**4,773,000**

Time Frame	30 years	100 years	500 years
Present Worth	$4,773,000	$5,453,000	$5,457,000

Sources: FS for WSOW (DA 1993) and Hood (1997).

F.6 REFERENCES FOR APPENDIX F

Delta Research Corporation, 1995, *Remedial Action Cost Estimating and Requirements System (RACER) User Manual*, Niceville, Fla.

DA: see U.S. Department of the Army.

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U.S. Environmental Protection Agency, 1993, *Revision to OMB A-94, Average Discount Rate for Beneficial Cost Analysis*, OSWER Directive 9355.3-20, Washington, D.C., June.

APPENDIX G:

ANALYTICAL METHODOLOGIES USED TO ADDRESS POTENTIAL ENVIRONMENTAL IMPACTS FOR ALTERNATIVE 2: MONITORING WITH NO ACTIVE REMEDIATION

APPENDIX G:

ANALYTICAL METHODOLOGIES USED TO ADDRESS POTENTIAL ENVIRONMENTAL IMPACTS FOR ALTERNATIVE 2: MONITORING WITH NO ACTIVE REMEDIATION

The U.S. Department of Energy (DOE) and the U.S. Department of Army (DA) are conducting an evaluation of potential alternatives for addressing groundwater contamination at the Weldon Spring Chemical Plant (WSCP) and the Weldon Spring Ordnance Works (WSOW), respectively, in St. Charles County, Missouri. This appendix discusses the analytical methodologies used to address potential environmental impacts for Alternative 2: Monitoring with No Active Remediation. The general methodology is explained for estimating physical hazards and airborne emissions during the construction and operational phases of Alternative 2.

G.1 PHYSICAL HAZARDS

The estimated number of worker fatalities and injuries associated with construction and operations were calculated on the basis of statistics available from the U.S. Bureau of Labor Statistics, as reported by the National Safety Council (1995), and on the basis of estimates of total worker hours and full-time equivalents (FTEs) required for construction and operational activities determined from the cost estimates (Appendix E) determined for this feasibility study (FS).

The specific rates used in the calculations were as follows: fatalities during construction, 15 per 100,000 workers; fatalities during operations, 4 per 100,000 workers; injuries during construction, 5.5 per 100 full-time workers; injuries during operations, 5.3 per 100 full-time workers.

Fatality and injury risks were calculated as the product of the appropriate incidence rate and the work hours expended during construction and operations (including both direct and indirect activities), which was then normalized by the number of work hours per day. The fatality and injury incidence during construction of additional monitoring wells equivalent to approximately 10% of the number of existing wells (i.e., about 15 additional wells) was estimated as follows:

$$
\begin{aligned}
(\text{Fatality/Injury Incidence})_{\text{construction}} = {} & (\text{Construction Work Hours}) \,/\, \{ (9 \text{ months per year}) \,/ \\
& (12 \text{ months per year}) \times (52 \text{ weeks per year}) \\
& \times [(6.5 \text{ hours per day}) \,/\, (8 \text{ hours per day}) \\
& \times (40 \text{ work hours per week})] \} \\
& \times (\text{Fatality/Injury Rate})_{\text{construction}},
\end{aligned}
$$

conservatively assuming that construction occurs only 9 months per year (due to winter or flooding) and might require the use of personal protective equipment (resulting in 6.5 hours of actual work per 8-hour workday). Construction activities associated with Alternative 2 are estimated to result in less than one case of occupational injury and no occupational fatalities, on the basis of a total of about 2,100 construction work hours.

The fatality and injury incidence during annual operations of additional monitoring wells was estimated as follows:

$$\begin{aligned}(\text{Annual Fatality/Injury Incidence})_{\text{operations}} = {} & (\text{Annual Operations Work Hours}) \,/ \\ & [\,(52 \text{ weeks per year}) \times (6.5 \text{ hours per day}) \,/ \\ & (8 \text{ hours per day}) \times (40 \text{ work hours per week})\,] \\ & \times (\text{Fatality/Injury Rate})_{\text{operations}},\end{aligned}$$

assuming that operations may require the use of personal protective equipment (resulting in 6.5 hours of actual work per 8-hour workday). Operational activities associated with the proposed monitoring wells are estimated to result in less than one annual case of occupational injury and no annual occupational fatalities, based upon a total of approximately 1,600 annual work hours.

The fatality and injury incidence during annual operations of the existing monitoring wells was estimated as follows:

$$\begin{aligned}(\text{Annual Fatality/Injury Incidence})_{\text{operations}} = {} & [\text{Annual Sampling Labor Costs (\$/yr)}] \,/ \\ & (\$100{,}000 \text{ per FTE}) \\ & \times (\text{Fatality/Injury Rate})_{\text{operations}},\end{aligned}$$

assuming an annual fully loaded labor cost of $100,000. (An approach different from that applied for the proposed monitoring wells was used to estimate the fatality and injury incidence for the existing monitoring wells due to the availability of specific cost data for the Weldon Spring area.) Operational activities associated with the existing monitoring wells are estimated to result in less than one case of annual occupational injury and no annual occupational fatalities, on the basis of an annual labor cost of approximately $270,000, which includes monitoring for both the DOE and the DA groundwater wells.

The calculation of fatalities and injuries from industrial accidents was based solely on historical industrywide statistics. The DOE and DA would implement best management practices

during any proposed construction and operational activities; therefore, fatality and injury incidence rates would be lower than the industrywide rates applied in this analysis.

G.2 AIRBORNE EMISSIONS OF CRITERIA POLLUTANTS

The emission rate factors used in calculating airborne emissions are presented in Table G.1. The criteria pollutants considered in this analysis included carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), and total suspended particulates (TSP). These pollutants would be emitted as the result of the combustion of diesel fuel and gasoline by equipment and vehicles. For this analysis, fugitive dust emissions during land clearing were assumed to be negligible (because of the limited land area that would be affected by monitoring well construction) and would be suppressed by watering and other containment methods, as needed.

G.2.1 Criteria Pollutant Emissions during Construction

Criteria pollutant emissions during the construction phase would consist primarily of emissions from construction equipment and worker vehicles. Estimating the quantities of these criteria pollutants requires data regarding (1) type and quantity of equipment to be used, (2) number of hours of operations, and (3) rate at which the pollutants would be emitted.

The types and quantities of equipment used during monitoring well construction were estimated by associating the individual activities within the construction cost estimate for Alternative 2 with the equipment required for that activity. (e.g., a flatbed truck with auger would be required during development of the 20-cm [8-in.] borehole for a 5-cm [2-in.] monitoring well.) This information was provided by the Remedial Action Cost Estimating and Requirements System (RACER) computer model (Delta Research Corporation 1995) used in the calculation of construction costs for this feasibility study (Appendix E) .

The operational time for construction activity "i" was determined by dividing the direct work force (in person-hours) by the appropriate crew size:

$$[\text{Operational Time (h)}]_i = [\text{Work Force (person-hours)}]_i \ / \ [\text{Crew Size (workers)}]_i .$$

For example, emplacement of a 2-m (5-ft) guard post made of cast iron and filled with concrete would require two laborers (i.e., the crew size in this case equals two).

TABLE G.1 Criteria Pollutant Emission Rate Factors

Pollutant	Construction Equipment [a] (lb/h)		Worker Vehicle [b] (g/km)
	Flatbed Truck	Post Driver	
Carbon monoxide (CO)	1.8	17	7.9
Hydrocarbons (HC)	0.19	0.56	1.4
Nitrogen oxides (NO_x)	4.2	0.41	1.3
Sulfur oxides (SO_x)	0.45	0.023	0.12
Total suspended particulates (TSP)	0.26	0.026	0.25

[a] Source: U.S. Environmental Protection Agency (EPA 1985).

[b] Source: U.S. Nuclear Regulatory Commission (NRC 1994).

Emission factors (lb/h) were obtained from EPA (1985) for the construction equipment identified within the construction cost estimate. The emission of pollutant "i" from construction equipment operations was estimated by the following:

$$[\text{Emission of Pollutant "i" (lb)}]_{\text{construction equipment}} = \sum_j \sum_k [\text{Operational Time (h)}]_{j,k} \times [\text{Emission Rate (lb/h)}]_{i,k},$$

by summing over all construction activities "j" and required construction equipment "k." Table G.2 shows the predicted emissions from equipment required for monitoring well construction.

Criteria pollutant emissions from construction worker vehicles were estimated assuming that the workday would be 8 hours and that each construction worker would travel to and from the construction site in a single vehicle. The number of one-way trips was calculated on the basis of total work hours (both direct and indirect activities) determined within the construction cost estimate for Alternative 2:

(Number of One-Way Trips) = (Total Work Hours) / (8 Hours per Workday)

TABLE G.2 Predicted Emissions from Equipment Required for Monitoring Well Construction

	Workday Average Emission Rate (lb/h)		Total Work Hours		Emissions (lb)
	Flatbed Truck	Post Driver	Flatbed Truck	Post Driver	
CO	1.8	1.7	278	31	1,000
HC	0.19	0.56	278	31	71
NO_x	4.2	0.41	278	31	1,200
SO_x	0.45	0.023	278	31	130
TSP	0.26	0.026	278	31	72
Aldehydes	0.11	0.020	278	31	32

For local impacts, it was assumed that the worker vehicles traveled 32 km (20 mi) to and from work or 64 km (40 mi) round-trip each day. The vehicular emissions of criteria pollutants were calculated as follows:

$$\begin{aligned}[\text{Emission of Pollutant "i" (lb)}]_{\text{worker vehicles}} = {} & (\text{Number of One-Way Trips}) \\ & \times \{2 \times [\text{One-Way Trip Distance (mi)}]\} \\ & \times (\text{lb}/453.59\ \text{g}) \times (1.609\ \text{km/mi}) \\ & \times [\text{Emission Factor (g/km)}]_i .\end{aligned}$$

The estimated values are provided in Table G.3.

In general, the total amount of criteria pollutant emissions was estimated to be relatively low (see Table G.4). The low emissions would result from the limited actions associated with monitoring well construction.

G.2.2 Criteria Pollutant Emissions during Operations

Airborne emissions of a given criteria pollutant "i" resulting from operations activities were calculated on the basis of the product of the number of auto one-way trips to the groundwater

TABLE G.3 Predicted Emissions from Construction Worker Vehicles

Potential Pollutant	Number of Auto One-Way Trips	Emission Factor (g/km)	One-Way Trip Distance (mi)	Emissions (lb)
CO	261	7.93	20	290
HC	261	1.35	20	50
NO_x	261	1.32	20	49
SO_x	261	0.12	20	4
TSP	261	0.25	20	9

TABLE G.4 Total Predicted Construction Emissions for Alternative 2: Monitoring with No Active Remediation

	Emissions (lb)		
Potential Pollutant	Construction Equipment	Worker Vehicles	Total
CO	1,000	290	1,300
HC	71	50	120
NO_x	1,200	49	1,200
SO_x	130	4	130
TSP	72	9	81

operable unit (GWOU) (for monitoring purposes), with a one-way trip distance (assumed to be 8 km [5 mi]) and the appropriate vehicular criteria pollutant emission rate factor from Table G.1:

$$\text{(Number of One-Way Trips)} = \text{(Total Number of Monitoring Wells)} \times \text{[Sampling Frequency (times per year)]} \;/\; \text{(Number of Wells Sampled per Trip)};$$

$$\text{(Annual Emission (lb/yr))}_i = \text{(Number of One-Way Trips)} \times \{\, 2 \times \text{[One-Way Trip Distance (mi)]} \,\} \times \text{(lb/453.59 g)} \times \text{(1.609 km/mi)} \times \text{[Emission Factor (g/km)]}_i \,.$$

The total number of monitoring wells was assumed to be 167 (152 existing plus 15 proposed). The sampling frequency would be annual (i.e., once per year), and only one well would be sampled during each trip (examination of recent groundwater sampling data for the GWOU indicates a median of three wells sampled per trip).

During operations, each worker was assumed to travel to and from the GWOU in a single vehicle (no car pooling), and the worker vehicles were assumed to travel 8 cm (5 mi) to and from the GWOU, or a 16-km (10-mi) round-trip. Emission factors (g/km traveled) were obtained from NRC (1994). (The difference in emission factors between those obtained from NRC [1994] and those obtained by running the EPA-approved vehicle emission models MOBILE 5a [EPA 1994a] and PART5 [EPA 1994b] was determined to be less than 10%.) The predicted annual emissions from vehicles used by monitoring workers are shown in Table G.5.

TABLE G.5 Predicted Annual Emissions from Vehicles Used by Monitoring Workers

Potential Pollutant	Total Number of Monitoring Wells	Sampling Frequency (times per year)	Number of Wells Sampled per Trip	Number of Auto One-Way Trips
CO	167	1	1	167
HC	167	1	1	167
NO_x	167	1	1	167
SO_x	167	1	1	167
TSP	167	1	1	167

Potential Pollutant	One-Way Trip Distance (mi)	Emissions Factor (g/km)	Annual Emissions (lb/yr)
CO	5	7.93	47
HC	5	1.35	8
NO_x	5	1.32	8
SO_x	5	0.12	1
TSP	5	0.25	1

G.3 REFERENCES FOR APPENDIX G

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